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TECHNICAL REPORT NO. 6-763

SHOCK-ABSORBING MATERIALS

Report 3

SELECTION OF A SUITABLE LOW-DENSITY CONCRETE FOR BACKPACKING FOR A PROPOSED FIELD TEST

by

G. C. Hoff

April 1968

Sponsored by

Defense Atomic Support Agency

Conducted by

U. S. Army Engineer Waterways Experiment Station
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Vicksburg, Mississippi

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ABSTRACT

The objective of this study was to investigate three insulating concretes being considered for use as a backpacking material to determine their handling, mixing, and placing characteristics, as well as the density variation, plastic shrinkage, aggregate segregation, and rate of hardening occurring in large sections made with each concrete, and to determine the problems that may be associated with the use of these concretes in a prototype situation.

Metal, half-scale model sections of a typical rock opening and tunnel liner were used in the study. The annular space of each section was pumped full or partially full of cellular, vermiculite, or polystyrene concrete. Each concrete was evaluated on the basis of ease of handling, batching, and placing and on the density variations occurring in both the unhardened and hardened condition of the concrete. In situ density variations were studied by the use of three techniques: ultrasonic pulse velocity, heat development, and hardened concrete samples. Fresh concrete unit weights were used for the unhardened concrete quality control. Rate-of-hardening tests were conducted to aid in the estimation of form-removal times. Methods of reducing plastic shrinkage and bleeding are discussed, along with other features such as handling and storage requirements of mixture components and suggested prototype batching and placing

equipment and techniques. An appendix describes a field placement trial of a cellular concrete arch section to determine the ease of placing and forming, required strength for arch to stand unsupported, and settlement of arch crown.

PREFACE

This study was conducted in the Concrete Division of the U. S. Army Engineer Waterways Experiment Station (WES) under the combined sponsorship of the Defense Atomic Support Agency (DASA), Test Command, Albuquerque, N. Mex., as part of Project Pile Driver, Operation Flintlock, Project 3.5, "Grouting and Materials Control," and DASA, Headquarters, Washington, D. C., as part of Nuclear Weapons Effects Research Subtask 13.010, "Response of Buried Structures to Ground Shock." DASA, Test Command, sponsored the actual laboratory work and preliminary analyses of the results and DASA, Headquarters, sponsored the final analyses of results and preparation of this report. The work was accomplished during the period November 1963 to April 1967 under the general supervision of Messrs. T. B. Kennedy, former Chief of the Concrete Division, and B. Mather, present Chief of the Concrete Division, and under the direct supervision of Messrs. J. M. Polatty, Chief of the Engineering Mechanics Branch, and W. O. Tynes, Chief of the Concrete and Rock Properties Section. Mr. George C. Hoff was the project leader and prepared this report.

Directors of the WES during the investigation and the preparation and publication of this report were COL Alex G. Sutton, Jr., CE, and COL John R. Oswalt, Jr., CE. Technical Director was Mr. J. B. Tiffany.

CONTENTS

TABLES

FIGURES

NOTATION

The principal symbols used in this report are listed below. Special-purpose subscripts and symbols are not listed but are explained in the text.

C = cement content, grams of cement per gram of concrete

e = base of natural logarithms = 2.71828

H = heat of hydration of the cement, calories per gram

L = length, feet

r = constant, depending on type of cement used

S = specific heat of the concrete, BTU/lb/F

t = time

T = temperature, $^{\circ}F$

CONVERSION FACTORS, BRITISH TO METRIC UNITS OF MEASUREMENT

British units of measurement used in this report can be converted to metric units as follows:

Multiply	By	To Obtain
inches	25.4	millimeters
feet	0.3048	meters
cubic yards	0.764555	cubic meters
cubic feet	0.02832	cubic meters
gallons	3.78533	liters
pounds	453.5924	grams
pounds per cubic foot	16.02	kilograms per cubic meter
pounds per square inch	0.070307	kilograms per square centimeter
feet per second	30.48	centimeters per second
British thermal unit	0.2520	kilogram-calories
Fahrenheit degrees	5/9	Celsius or Kelvin degrees[a]
square inches	6.4516	square centimeters
BTU/lb/F	1.000	cal/gram/C

[a] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.16$.

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Interest in the use of backpacking for shock isolation of entire buried structures has generated many ideas as to the feasibility and composition of various materials and material systems that might be satisfactorily used as backpacking. A wide variety of materials can be fabricated to meet the design criteria for backpacking as dictated by jobsite conditions, but in most cases the in-place cost of these materials is prohibitive (Reference 1).

In November 1961, the U. S. Army Engineer Waterways Experiment Station (WES) initiated a program under the sponsorship of the Defense Atomic Support Agency to develop low-cost, easily placed construction materials for use as backpacking for deeply buried structures in rock. This program, entitled "Shock-Absorbing Materials," has resulted in the development of various insulating concretes[1] (References 1, 2, and 3), such as cellular concrete, vermiculite concrete, and polystyrene concrete, having compressive

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[1] Insulating concretes are best defined as concretes made with portland cement, water, air, and possible aggregate additions to form a hardened material that will have an oven-dry density of 50 pcf or less.

crushing stress plateaus to 40 percent deformation, ranging from 50 to 600 psi,[2] and which can be easily handled and placed in tunnel environments at a cost considerably less than other materials being considered for the same purpose. Results of additional studies pertaining to the development of a better understanding of the backpacking concept, which were also generated by this program, can be found in References 4 to 7.

The initial development of insulating concretes for use as backpacking (References 2 and 3) was limited to the evaluation of closely controlled, laboratory-cast concrete specimens. The study reported herein is expected to extend the knowledge gained in the previous programs and to investigate some of the problems that may be associated with the use of these concretes in prototype construction.

1.2 OBJECTIVE

The objective of this study was to investigate three insulating concretes, developed in earlier studies, and which are being considered for use as backpacking to determine their handling, mixing, and placing characteristics as well as the density variation, plastic shrinkage, aggregate segregation, and rate of hardening occurring in large sections made with each concrete, and to determine the problem

[2] A table of factors for converting British units of measurement to metric units is presented on page 13.

areas that may be associated with the use of these concretes in a prototype situation.

1.3 SCOPE

To accomplish the objective of this study, half-scale, metal models of a section of a typical rock opening and tunnel liner contemplated for use in a proposed field test were fabricated and assembled. The annulus provided by the configuration of this form was pumped full or partially full of three types of backpacking concrete. In all, four separate operations were conducted during the program and will be referred to throughout the remainder of this report as (1) preliminary placing operation, (2) cellular concrete placing operation, (3) vermiculite concrete placing operation, and (4) polystyrene concrete placing operation. Cellular concrete was used in the preliminary placing operation in order to work out the equipment and procedural difficulties. The cellular, vermiculite, and polystyrene concrete were then placed in the forms, evaluated, and compared on the basis of ease of handling, mixing, and placing; density variation; plastic shrinkage; aggregate segregation; and rate of hardening. Based on this evaluation and consideration of such other features as availability of the material, storage requirements, and cost, the selection of one of the three concretes for use as backpacking in the proposed field test was made, as described in

Appendix A. A field trial placement operation using the selected concrete was then conducted and is also reported in Appendix A.

CHAPTER 2

MATERIALS, EQUIPMENT, AND PROCEDURES

2.1 MATERIALS

2.1.1 Portland Cement. The portland cement (RC-560) used for this phase of the program met the requirements for Type III and had the following chemical and physical characteristics:

Chemical Analysis		Physical Properties	
Constituents	Percent		
SiO_2	21.1	Normal consistency	27.2
Al_2O_3	4.8	Setting time, Gillmore, hours:minutes	
Fe_2O_3	4.0	Initial	3:20
CaO	64.6	Final	6:50
MgO	1.8	Autoclave expansion, pct	0.0
SO_3	2.4	Air content of mortar, pct	7.2
Ignition loss	1.4	Compressive strength of mortar, psi	
Total	100.1		
Insoluble residue	0.01	1 day	2,390
Na_2O	0.13	3 days	3,810
K_2O	0.23	7 days	5,165
Total alkalies as Na_2O	0.28	Surface area, air permeability fineness (Blaine), cm^2/g	4,790

(Continued)

Chemical Analysis		Physical Properties	
Constituents	Percent		
C_3A	5.9	Specific gravity	3.13
C_3S	57.74	Particle diameter, percent finer than	
C_2S	16.93	60 microns	97.0
C_4AF	12.17	55 microns	95.2
		50 microns	94.0
		45 microns	91.9
		40 microns	90.9
		35 microns	88.3
		30 microns	84.9
		25 microns	81.7
		20 microns	75.8
		15 microns	66.8
		10 microns	45.8
		7.5 microns	34.6
		Fineness, percent passing	
		No. 200 sieve	99.1
		No. 325 sieve	97.0
		Heat of hydration, cal/g	
		7 days	80.81
		28 days	91.44

2.1.2 Vermiculite Aggregate. Vermiculite is a hydrated magnesium-aluminum-iron silicate that is thermally exfoliated in special furnaces to form a lightweight expanded aggregate. The aggregate used in this study (designated SM-25 in this report) is known as vermiculite standard-grade No. 3 and is normally used for plastering and insulating concrete operations. Bulk density of the expanded aggregate was 8.0 pcf and its gradation (as received) was as follows:

Sieve Analysis (As-Received)

Sieve No.	Size Opening	Cumulative Percent Passing
	inches	
4	0.187	100.0
8	0.0937	95.8
16	0.0469	49.7
30	0.0232	15.2
50	0.0117	7.6
100	0.0059	3.4
200	0.0029	1.5

2.1.3 Polystyrene Aggregate. The usual practice in manufacturing polystyrene beads is to polymerize styrene, which contains a blowing agent (C_5 to C_7 saturated hydrocarbons) in an aqueous emulsion. The resulting products are granules or beads of unexpanded polystyrene. The application of one of a number of thermal processes to the unexpanded beads causes the volatilization of the blowing agent present in the unexpanded granules, thus causing expansion into

a bead form. The type of thermal process used and its control determine the final density of the expanded bead. The polystyrene beads used as aggregates in this program (designated SM-21) were expanded commercially using an infrared heating system with a resulting expanded density of 3 pcf. A typical analysis of the unexpanded beads is as follows:

Typical Analysis of Unexpanded Polystyrene	
Bulk density, pcf	38
Real density, pcf	65.6
Moisture, pct	0.05 to 0.10
Monomer content, pct	0.1 to 0.2
Relative viscosity (1 pct in toluene)	2.0 to 2.1
Volatile content, pct	5.0 to 6.0
Blowing agent	n-pentane or isopentane

The expanded beads were both white and colored, nonself-extinguishing pellets with the following physical properties:

Actual Analysis of Expanded Polystyrene	
Real density, pcf	67.00
Expanded density, pcf	3.00
Bead colors	White and blue

Sieve Analysis

Sieve No.	Size Opening	Cumulative Percent Passing
	inches	
4	0.187	100.0
8	0.0937	17.5
16	0.0469	0.0

2.1.4 Foaming Agent Used in the Cellular Concrete. A foaming agent, AD-186, was used to provide the stable air-bubble system necessary for the fabrication of cellular concrete. A spectroscopic analysis of the foaming agent indicated the presence of decomposition products of proteins reacted with aliphatic fatty acids or salts of fatty acids. The manufacturer refers to his product as a hydrolyzed stabilized protein foaming agent.

For use, a premixed solution of a predetermined concentration of foaming agent and water was prepared. The solution was then placed in a pressure container and subjected to a controlled air pressure. The air pressure forced the solution through a discharge line into a blending nozzle which agitated the solution and combined it with compressed air. The resulting product that issued from the blending nozzle was a stable, preformed foam having the consistency of shaving cream obtained from aerosol cans. This preformed foam provides the stable air-bubble system in the cellular concrete. The foaming equipment is shown in Figure 2.1.

2.1.5 Air-Entraining Admixtures. To facilitate placement, an air-entraining admixture was required in the vermiculite and polystyrene concrete mixtures. The admixture used was laboratory stock, AEA-535, neutralized vinsol resin solution.

2.2 MIXTURE DESIGNS

The backpacking concrete mixture designs were developed during

laboratory studies of shock-absorbing concretes which were in progress at the time this program was begun. As stated earlier, three types of backpacking concrete were proportioned for use in this program: cellular, vermiculite, and polystyrene. The cellular concrete uses no aggregate, with air providing the cellular structure. The vermiculite concrete uses as aggregate a naturally occurring material that has been expanded. The polystyrene concrete uses as aggregate a plastic material that has been expanded. Figure 2.2 shows enlarged views of typical sawed surfaces of each type of concrete. In the proportioning of each of the concretes, no attempt was made to relate the different types on the basis of physical characteristics.

2.2.1 Cellular Concrete. Cellular concrete was used in both the preliminary placing operation performed to resolve equipment and procedure difficulties and in the test of the simulated tunnel. The neat-cement cellular concrete was designed to have a cement content of 4.83 bags/cu yd, a water content of 11.27 gal/bag of cement, and an air content of 64.4 percent. Two tub grout mixers (described in Section 2.3) of identical batch-size capacities were used in the preliminary placing operation, while two horizontal-drum paddle mixers of different capacities were used in the test placement. Thus, three mixture proportions were used, as follows:

Material	Solid Volume	Dry Batch Weight
	ft^3	pounds
Mixture 1, Preliminary Placing Operation:		
Portland cement, Type III	0.410	80
Water	1.132	70.5
Foam solution	0.149	9.3
Average unit weight = 33.2 pcf		
Mixture 2, Cellular Concrete Operation, Large Paddle Mixer:		
Portland cement, Type III	0.482	94
Water	1.324	82.5
Foam solution	0.161	10.5
Average unit weight = 33.8 pcf		
Mixture 3, Cellular Concrete Operation, Small Paddle Mixer:		
Portland cement, Type III	0.380	74.2
Water	1.059	66
Foam solution	0.135	8.4
Average unit weight = 33.8 pcf		

2.2.2 Vermiculite and Polystyrene Concretes. The vermiculite and the polystyrene concretes were proportioned on the basis of a cement-aggregate ratio (cubic foot of loose cement per cubic foot of loose aggregate) and a water-aggregate ratio (gallons of water per cubic foot of loose aggregate). During the vermiculite concrete placing operation, only one horizontal-drum paddle mixer was used. However, during placement of the first lift of polystyrene concrete two of these mixers with different batch-size capacities were used.

For the second lift of polystyrene only one mixer was used and the water-aggregate ratio was changed, while the cement-aggregate ratio remained the same. The actual mixture proportions used were as follows:

Material	Solid Volume	Dry Batch Weight
	ft^3	pounds
Mixture 4, Vermiculite Concrete Operation:		
Portland cement, Type III	0.242	47.2
Vermiculite aggregate No. 3	4.00[a]	32.0
Water	1.926	120.0
Air-entraining admixture	0.001	158 ml
Cement-aggregate ratio = 0.125		
Water-aggregate ratio = 3.6		
Average unit weight, pcf = 45.7		
Air content, pct = 27 to 30		
Mixture 5, Polystyrene Concrete Operation, Lift 1, Large Paddle Mixer:		
Portland cement, Type III	0.410	80
Expanded polystyrene aggregate	4.00[a]	7.2
Water	1.284	80
Air-entraining admixture	0.001	160 ml
Cement-aggregate ratio = 0.213		
Water-aggregate ratio = 2.4		
Average unit weight, pcf = 30.2		
Air content, pct = 22 to 26		
Mixture 6, Polystyrene Concrete Operation, Lift 1, Small Paddle Mixer:		
Portland cement, Type III	0.308	60
Expanded polystyrene aggregate	3.00[a]	5.4

(Continued)

[a] Loose volume.

Material	Solid Volume	Dry Batch Weight
	ft^3	pounds
Mixture 6, Polystyrene Concrete Operation, Lift 1, Small Paddle Mixer (Continued):		
Water	0.963	60
Air-entraining admixture	0.001	120 ml
Cement-aggregate ratio = 0.213		
Water-aggregate ratio = 2.4		
Average unit weight, pcf = 30.2		
Air content, pct = 22 to 26		
Mixture 7, Polystyrene Concrete Operation, Lift 2:		
Portland cement, Type III	0.359	70.1
Expanded polystyrene aggregate	3.50[a]	6.3
Water	0.706	44
Air-entraining admixture	Negligible	80 ml
Cement-aggregate ratio = 0.213		
Water-aggregate ratio = 1.51		
Average unit weight, pcf = 31.7		
Air content, pct = 14 to 17		

[a] Loose volume.

2.3 MIXING AND PLACING EQUIPMENT

The two tub mixers used during the preliminary placing operation were powered by a vane drive air motor affixed on top of the mixer. The mixing action was provided by two sets of blades set on the drive shaft from the air motor at depths suitable to provide a high shear mixing action when in operation.

The concretes investigated during this phase of the work were pumped into the corrugated metal form simulating the tunnel through

a 2-inch-diameter hose by means of an open-throat, positive displacement pump. The large open throat of the pump permits substantial volumes of material to be deposited directly on an auger feed mechanism that propels the concrete into the rotor-stator pumping elements of the pump and then into the hose. The pump is capable of placing 3 cubic feet of concrete per minute providing the aggregate does not exceed 1/4 inch in size. This output was adequate for the needs of this program. One of the tub mixers and the positive displacement pump are shown in Figure 2.3a.

Two horizontal-drum paddle mixers having different batch-size capacities were used for the cellular, vermiculite, and polystyrene concrete placing operations. The batching setup for the paddle mixers is shown in Figure 2.3b.

2.4 FORMWORK

As mentioned in Section 1.2, metal forms simulating at half scale a typical rock opening and tunnel liner that may be used in proposed field tests were used as the formwork for the three types of concrete. The outer portion of the form represented the rock opening, and was made of corrugated sheet metal with an 8-foot inside diameter. The inner portion of the form, representing the tunnel liner, was a smooth-wall culvert with a 4-foot inside diameter. The ends, or bulkheads, of the formwork were made of steel plate.

The entire form was fabricated in three 9-foot-long sections, as shown in Figure 2.4a, to facilitate ease of handling and stripping. Figure 2.4b shows the entire assembled formwork.

2.5 MIXING AND PLACING PROCEDURES

2.5.1 Preliminary Placing Operation. The preliminary placing operation was initiated to work out any problems with the formwork, fabricating equipment, and placing techniques. Cellular concrete was chosen as the material to be placed because of its lower cost compared with the other two materials also under consideration. Horizontal-drum paddle mixers were to be utilized, but were not available at the start of this phase of the work; consequently, two tub mixers were substituted.

The mechanical pore formation of the cellular concrete is provided by introducing a preformed stable foam (described in Section 2.1.4) into a portland-cement slurry and blending the two until the foam is uniformly dispersed. In batching the concrete, the required batch water is placed in the mixer, then the cement is added and mixed until a uniform slurry is obtained. The discharge nozzle from the foam generator discharges foam at a constant volume rate. By using a stopwatch to time the amount of discharge, any desired volume of foam, and hence air content, can be introduced into the slurry. The foam and slurry were blended for 150 seconds after the foam discharge had stopped.

When using tub mixers for fabricating cellular concretes with very high air contents such as those used in this program, the speed at which the drive shaft is turned by the variable-speed air motor should be very carefully controlled. Variations in the mixing speed from batch to batch may cause enough variation in the final density of the individual batches of concrete that the density variation obtained between batches may exceed the allowable variation for density control contained in job specifications. The constant-speed, horizontal-drum paddle mixer has been proven in the WES laboratory to be more efficient for this type of operation.

The two tub mixers were operated in such a manner as to provide a constant flow of cellular concrete into the formwork. Two one-third sections of the formwork were assembled for this operation and were partially submerged in a bed of sand (see Figure 2.5) for support.

Two lifts of concrete were placed in the form. The first lift was pumped through a 2-inch-diameter rubber hose into the bottom of the form and allowed to flow upward for a distance of approximately 30 inches before the first lift was completed. The second lift was placed seven days later, first by filling the left side of the remaining annulus and then by filling the right side. The sampling schedule for the preliminary placing operation (Figure 2.6) shows the approximate location of the two lifts.

The original plans for the preliminary placing operation called for a complete section of cellular concrete to be placed; however, an attempt to place the last section of the formwork on the assembled portion was not successful as some differential movement had occurred between the ends of the assembled portion which prevented fastening the final section to the formwork. The first lift was allowed to cure 14 days before the forms were removed.

2.5.2 Cellular Concrete Placing Operation. For the actual test, the entire formwork was assembled indoors, as shown in Figure 2.4b, for the cellular concrete placing operation. The same batching procedure used in the preliminary placing operation was used except that the tub mixers were replaced with the horizontal-drum paddle mixers. A mixing time of 3 minutes after the foam had been added was used with these mixers.

Three lifts of concrete, as shown in Figure 2.7, were used to fill the form. The first lift was approximately 30 inches high and filled the annulus to a point where no communication was possible under the bottom of the inner form between the two sides of the remaining annulus. The second lift was placed four days later and filled both sides of the annulus to a point approximately 10 inches above the top of the inner form. The third and final lift was placed four days after the second and filled the remaining annulus. The forms were removed 14 days after the placing of the first lift.

Figure 2.8 shows the hardened concrete after the bulkheads had been removed from the form.

2.5.3 Vermiculite Concrete Placing Operation. Only the smaller horizontal-drum mixer was used during the placing of the three lifts of vermiculite concrete. The batching sequence for this operation was as follows: (1) All the water and air-entraining admixture were added to the mixer and mixed for 30 seconds. (2) All the cement was then added and mixed for an additional 30 seconds. (3) Finally, all the aggregate was added and the entire batch mixed for an additional 2 minutes.

The first lift was placed to a point 6 inches above the bottom of the inner form. Four days later, the second lift was placed to a point 10 inches above the top of the inner form. The third and final lift was placed four days after the second and filled the remaining annulus. The sampling schedule, Figure 2.9, shows the approximate location of the lifts. The formwork was stripped 14 days after the placing of the first lift. Figure 2.10a shows an end view of the hardened vermiculite concrete mass after the bulkhead had been removed from the form.

2.5.4 Polystyrene Concrete Placing Operation. Both horizontal-drum paddle mixers were used to place the first lift of polystyrene concrete; only the smaller of these mixers was used to place the second lift. The batching sequence for the polystyrene concrete was

the same as that of the vermiculite concrete.

The first lift was placed to a point 6 inches above the bottom of the inner form. Observation of the discharge from the end of the 2-inch-diameter rubber hose revealed that during the pumping the polystyrene aggregate was segregating from the cement paste. The water content was reduced in the second lift of polystyrene concrete to eliminate some of this segregation. The left side of the second lift was placed to a point approximately 4 inches above the top of the inner form, whereas the right side of the lift did not quite reach the top of the inner form. The second lift was placed four days after the first lift.

In view of the placing difficulty encountered during the first two lifts, the remaining annulus was not filled with a third lift. The approximate lift locations can be seen in Figure 2.11. Figure 2.10b shows an end view of the second lift of the hardened polystyrene concrete mass with the bulkhead partially removed. The forms were removed 14 days after the placing of the first lift.

2.6 SAMPLING EQUIPMENT AND PROCEDURES

2.6.1 Compressive Strength Samples. During all four placing operations, 6-inch-diameter by 12-inch-long concrete cylinders were made randomly throughout the batching and pumping operations. Samples were taken at the mixer(s) because of the inaccessibility of

the discharge end of the grout hose being used. All cylinders were made in accordance with the procedures outlined in CRD-C 10-61 (Reference 8) for compressive strength samples with the exception of the cellular concrete cylinders which were not hand-rodded or vibrated. The polystyrene and vermiculite concrete cylinders were hand-rodded.

All the compressive strength cylinders were allowed to cure 48 hours in the mold at which time the molds were stripped, the concrete cylinders sealed in polyethylene bags, and stored at 73 F until testing.

<u>2.6.2 Rate-of-Hardening Samples</u>. Rate-of-hardening samples were taken in accordance with CRD-C 86-64 (Reference 8). The rate-of-hardening tests began on each sample shortly after it was made and were conducted on the material while it was still in the mold. Between tests on each sample, the sample was covered with a sheet of polyethylene to prevent moisture loss from the concrete due to evaporation. Samples were stored at 73 F.

<u>2.6.3 Hardened Density Samples</u>. Hardened density samples were obtained from the hardened mass of concrete cast in each operation. The masses of concrete were first roughly sawed with either a hand-operated crosscut saw (cellular concrete, Figure 2.12a) or a powersaw (vermiculite and polystyrene concrete, Figure 2.12b) into long wedges as shown in Figure 2.13a. These wedges were numerically labeled as

denoted on the sampling schedules shown in Figures 2.6, 2.7, 2.9, and 2.11. The wedges were then sliced into wedge-shaped blocks (Figure 2.13b) which were alphabetically labeled. With this labeling system, a sample labeled C6 came from the portion of concrete delineated by the two cuts normal to the centerline of the section and labeled C, and the wedge-shaped portion of C slice denoted as 6. Each of these roughly cut blocks was then trimmed to an 8-inch cube using a circular, diamond-tooth powersaw. Figure 2.14a shows the finished polystyrene concrete cubes with the powersaw in the background.

2.7 TESTING EQUIPMENT AND PROCEDURES

2.7.1 Hardened Density Determinations. The 8-inch cubes resulting from the sampling of the hardened concrete mass from each placing peration were dried in a gas oven at 220 F until a constant weight was obtained. A constant weight was defined as less than 0.5 percent loss in weight between successive 24-hour readings. Normally the constant weight was obtained in 72 hours of drying; however, in a few instances involving the vermiculite concrete, an additional 24 hours of drying was required before the constant weight was attained.

When it was discerned that a cube had reached a constant weight (by definition), the weight was immediately recorded and the cube

allowed to cool for 2 hours before any of its dimensions were measured. The volume of each cube was determined by using a caliper and a steel rule calibrated to one-hundredth of an inch. The average dimensions of height, width, and depth were measured and the volume of the cube was computed. The density in pounds per cubic foot was calculated from the weight and volume of each cube.

2.7.2 Compressive Strength Tests. The 6-inch-diameter by 12-inch-long concrete cylinders cast during each placing operation, with the exception of the preliminary placing operation, were used in the compressive strength testing. The top and bottom 3 inches of each cylinder were trimmed off by means of a circular, diamond-tooth powersaw. The remaining 6-inch by 6-inch cylinder was used in a constrained compression test. In a constrained compression test there is no appreciable radial strain; the sample is loaded only in the uniaxial direction with all deformations occurring in that same direction as the sample is confined in a thick-wall testing chamber. In this investigation, the 6-inch-diameter surface of the sample was loaded by a 4-inch-diameter loading piston in order to minimize the sidewall friction effects. Each sample was loaded at a constant straining rate of 3 percent strain per minute using a 30,000-pound universal testing machine (Figure 2.15).

Loads were measured by a recording load cell. Deformations were recorded by means of a slide-wire potentiometer affixed to the

base platform of the testing machine and the moving loading piston. The resulting data were plotted in curve form using an X-Y recorder, with load coordinates being transformed into coordinates of stress over the 4-inch-diameter loading piston area on the Y-axis and deformation on the X-axis.

Samples from the cellular and vermiculite concrete were tested at various ages to 28 days in both the as-cast and cured conditions and also in an oven-dry condition. Additional moist-cured samples of the vermiculite concrete were tested at 60 and 90 days age. Seventy-two hours prior to the testing of samples in the oven-dry condition, the samples to be tested were removed from the polyethylene bags in which they were stored and dried at 220 F until 4 hours before testing. The samples were then allowed to cool at room temperature until actual testing began.

It was impossible to test the polystyrene concrete cylinders because of the aggregate segregation that had occurred. Figure 2.14b shows three polystyrene samples of varying degrees of segregation. The light beads floated out of the cement paste, leaving the paste to form a hard layer at the bottom of the cylinder. Only two samples of polystyrene concrete were tested at 28 days in the as-cast and cured condition.

2.7.3 Rate-of-Hardening Tests. The rate-of-hardening test was employed to determine the hardening characteristics of each mixture

design used during this phase of the work, and was conducted in accordance with CRD-C 86-64 (Reference 8).

Prior to start of the test on each sample, all excess moisture was removed by means of a pipet. A No. 8 Proctor needle with a 1.003-in^2 surface area was used as the loading surface. The needle was forced gradually and uniformly downward into the sample to a depth of 1 inch. The force required to embed the needle to this depth was recorded directly in pounds per square inch. The penetration tests were made at 2-hour intervals when possible for a 48-hour period and then randomly until 90 hours had elapsed since the sample was cast.

2.7.4 Ultrasonic Pulse Velocity Tests. Ultrasonic pulse velocities were determined in accordance with CRD-C 51-57 (Reference 8) for the hardened mass of both the cellular and vermiculite concrete.

Figure 2.16 shows the equipment used in this operation and its actual use on the cellular concrete mass. Figure 2.17 shows the locations of points used as sending and receiving stations on the exposed end surfaces of the concrete. The metal inner and outer forms were left on the concrete during all of the readings that were made on both of the entire hardened masses.

2.7.5 Heat-Development Tests. An array of thermocouples was placed in the annulus of the formwork prior to the start of each placing operation except the preliminary placing operation. The

locations of these thermocouples are shown in Figures 2.18, 2.19, and 2.20. Temperatures were recorded on a continuous 12-channel recorder for all thermocouples in the annulus and for four ambient-temperature recording thermocouples, two of which were located at the inside wall of the inner form and two at the outside wall of the outer form. Temperatures were recorded for only the first lift of the polystyrene concrete placing operation.

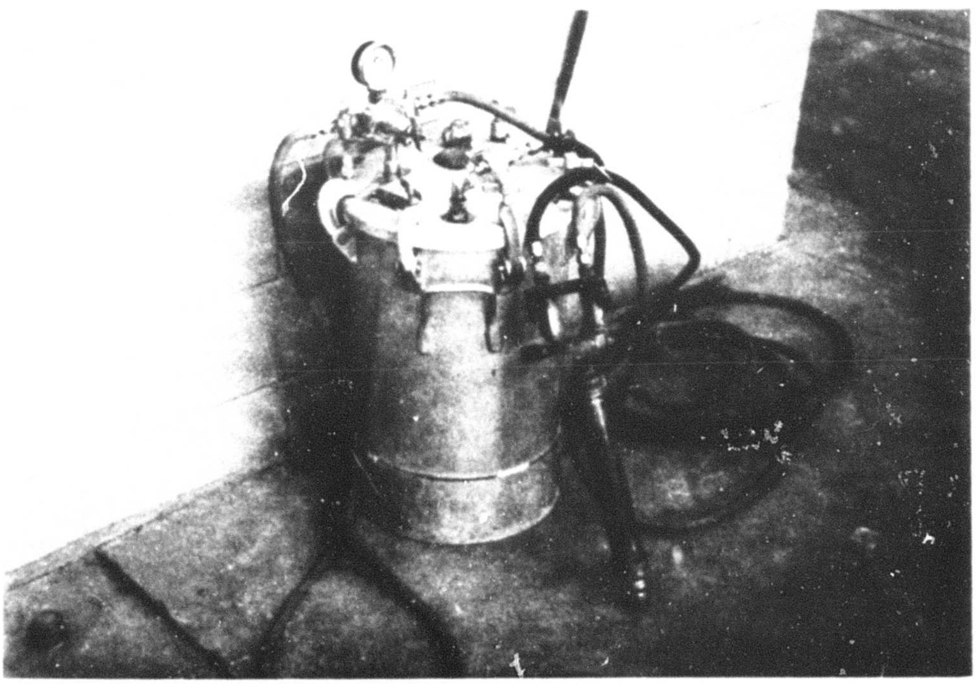


Figure 2.1 Cellular concrete foam equipment.

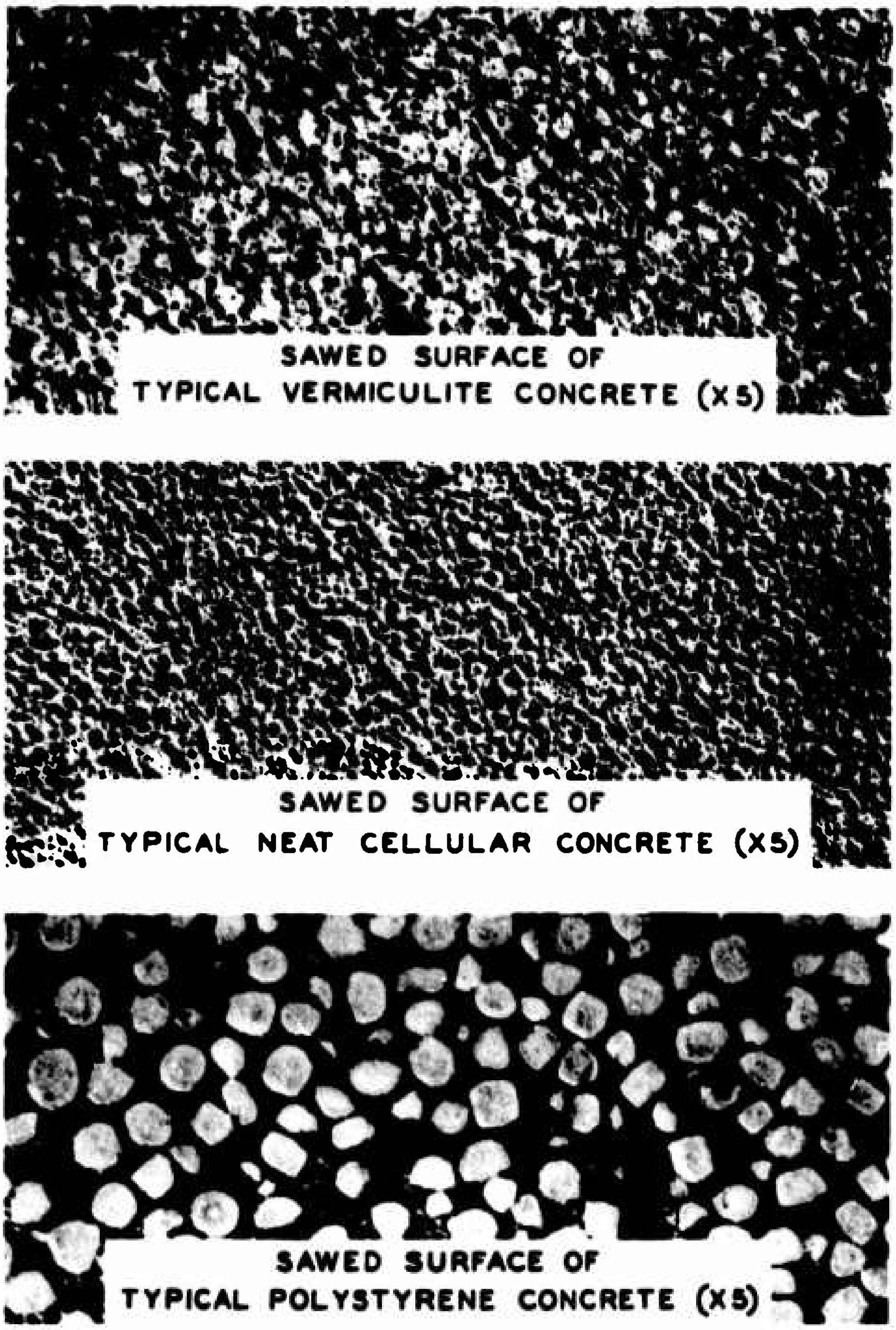
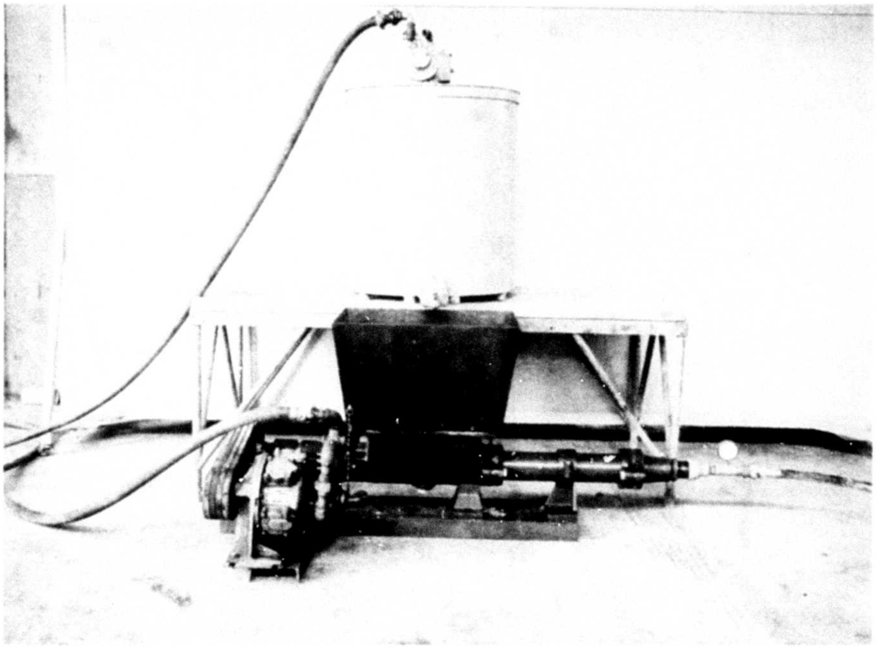
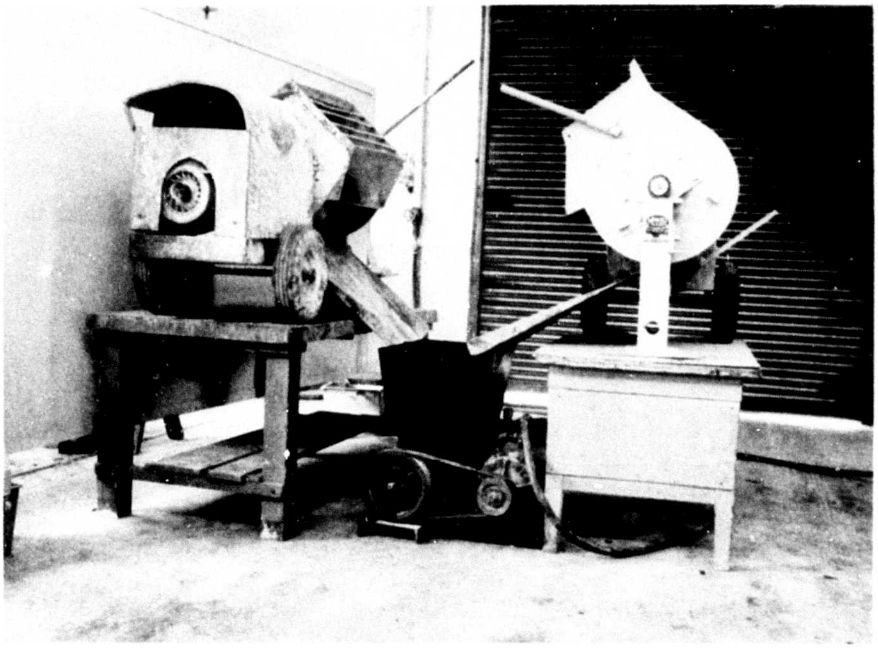


Figure 2.2 Sawed surfaces of a typical vermiculite, cellular, and polystyrene concrete.

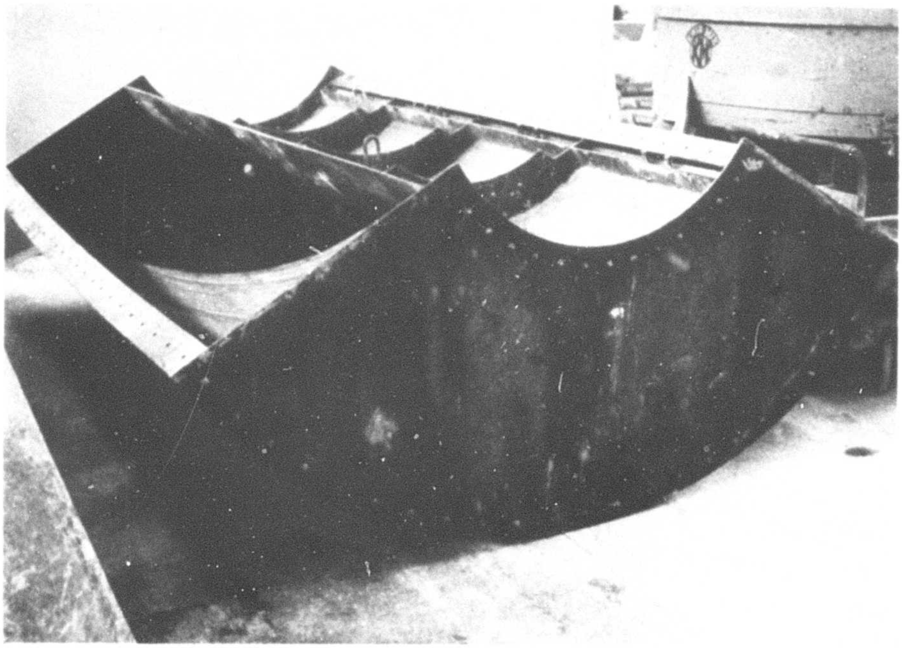


a. Tub mixer and pumping equipment.

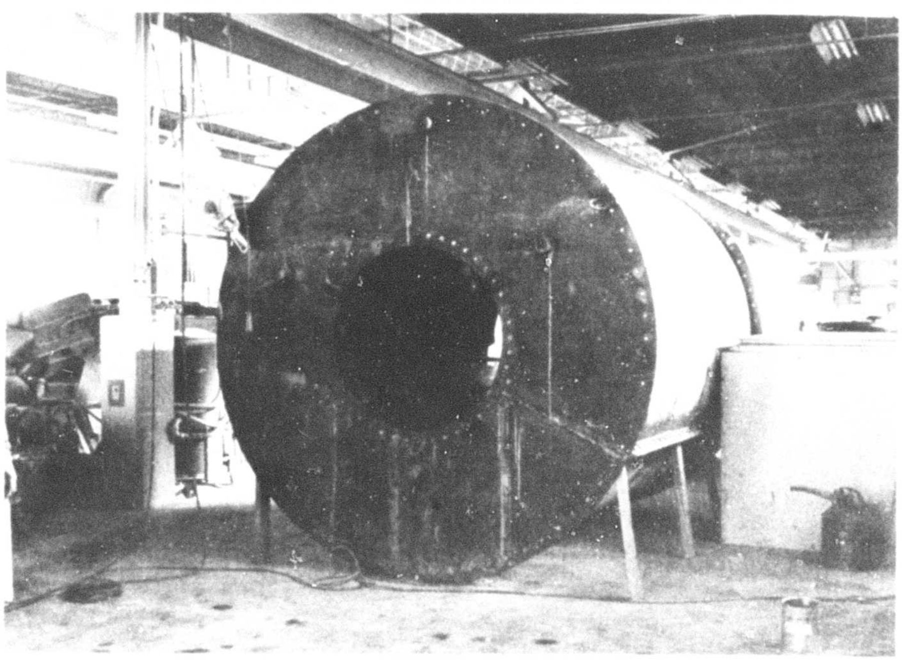


b. Paddle mixers and pumping equipment.

Figure 2.3 Mixers and pumping equipment.



a. One-third section of formwork.



b. Complete assembled formwork.

Figure 2.4 Views of formwork simulating rock tunnel and tunnel liner.

Figure 2.5 Preliminary placing operation formwork.

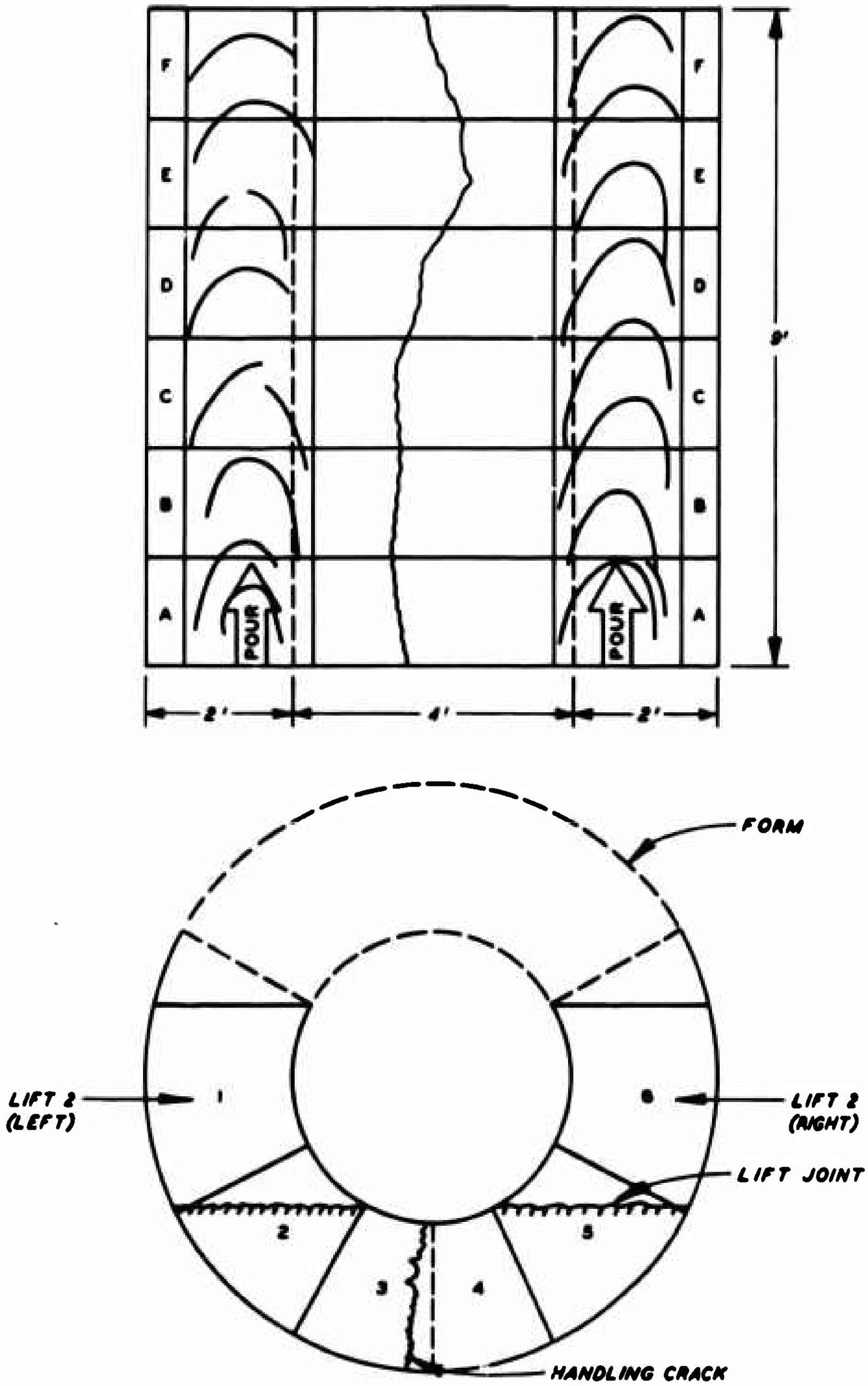


Figure 2.6 Sampling schedule for cellular concrete preliminary placing operation.

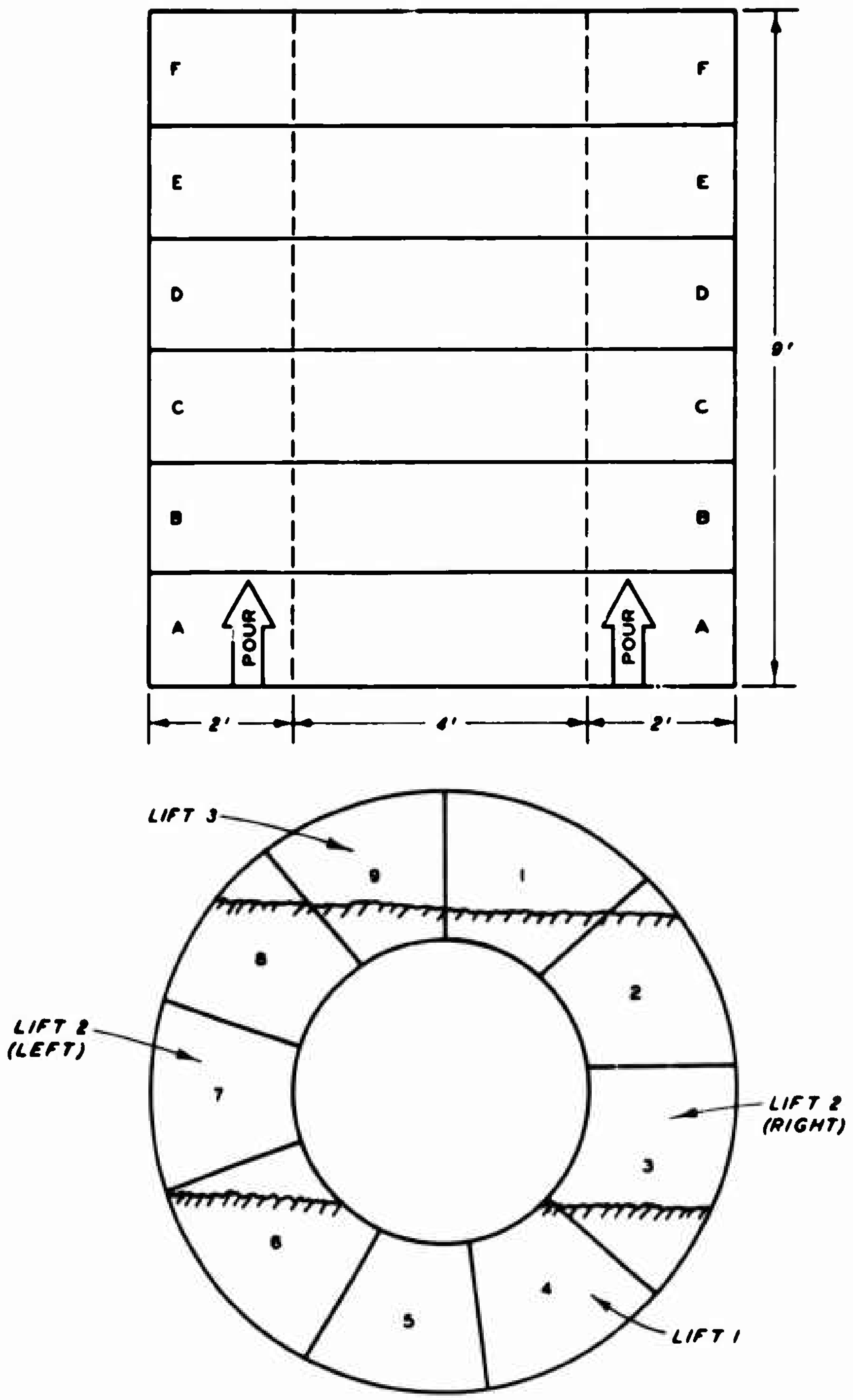


Figure 2.7 Sampling schedule for cellular concrete placing operation.

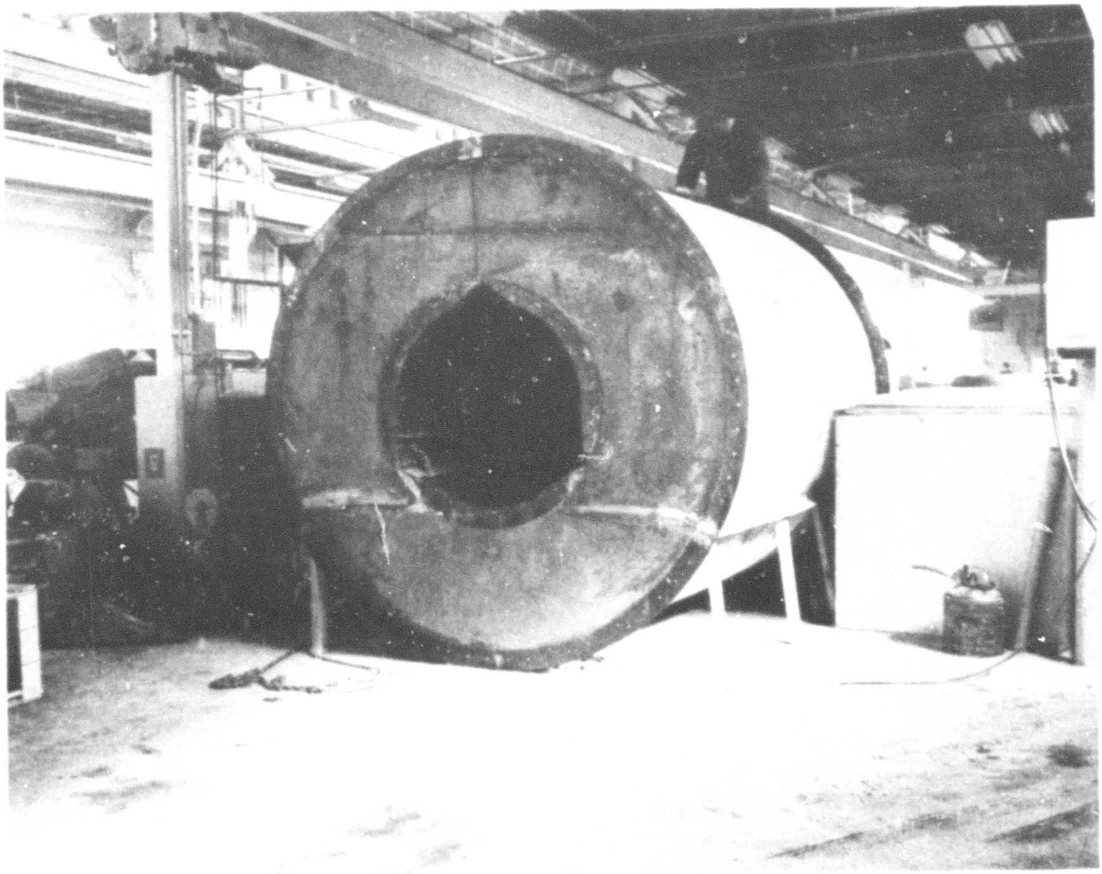


Figure 2.8 End view of cellular concrete section.

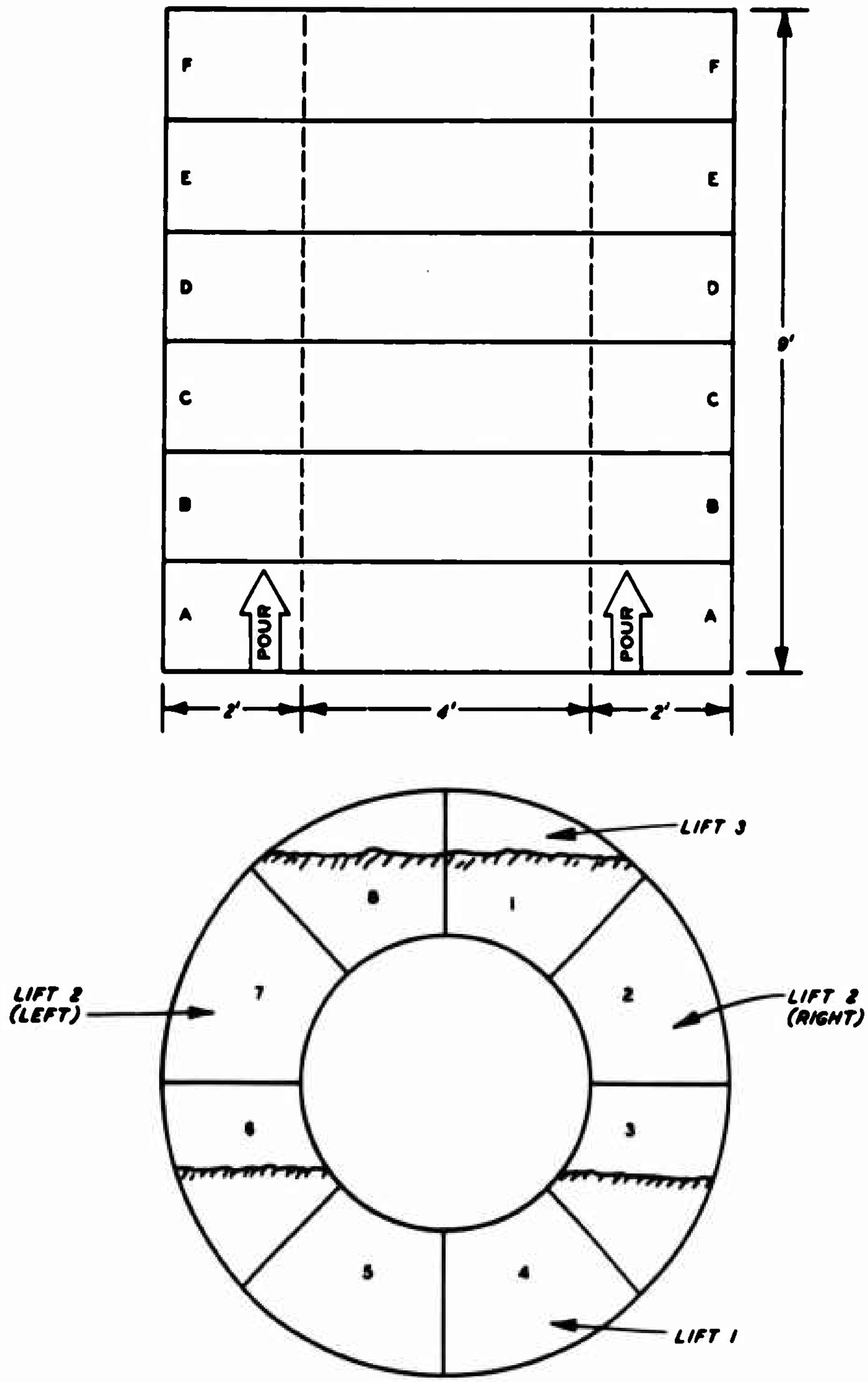
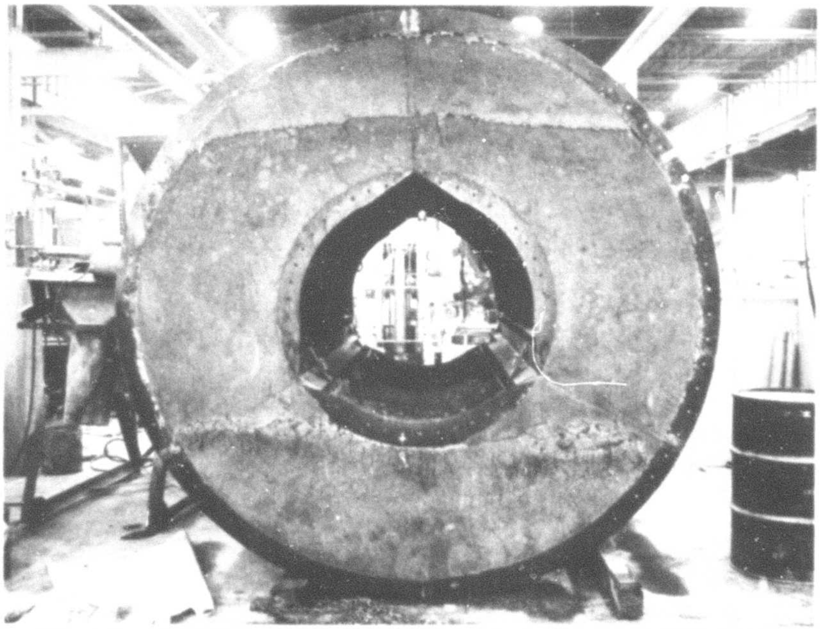
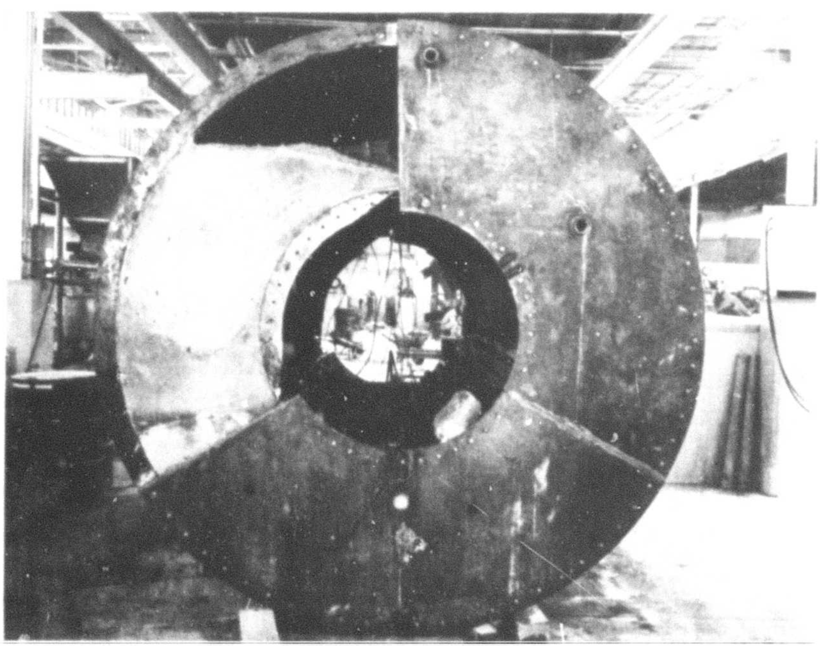


Figure 2.9 Sampling schedule for vermiculite concrete placing operation.



a. Vermiculite concrete section.



b. Polystyrene concrete section.

Figure 2.10 End views of vermiculite and polystyrene concrete sections.

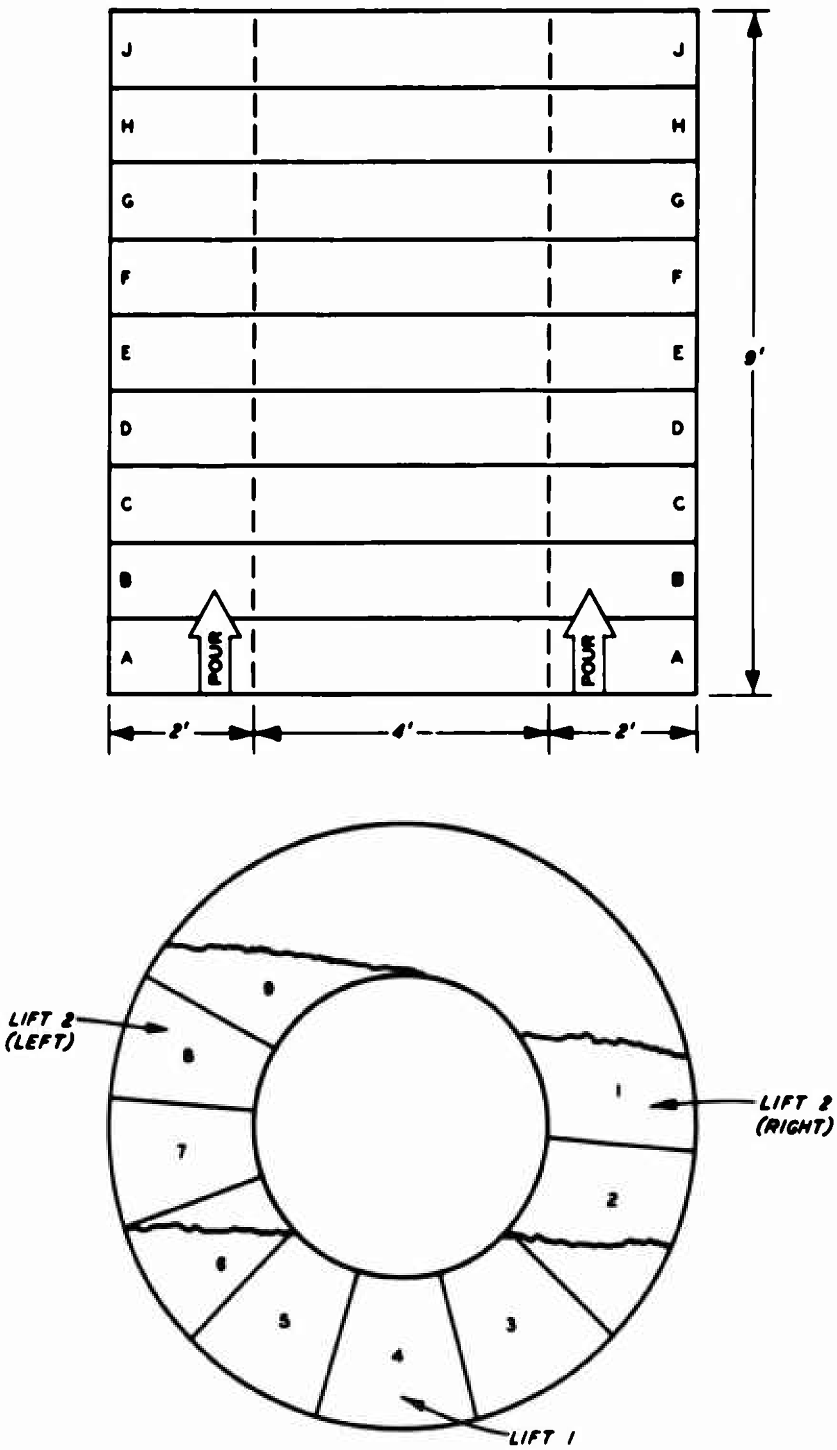
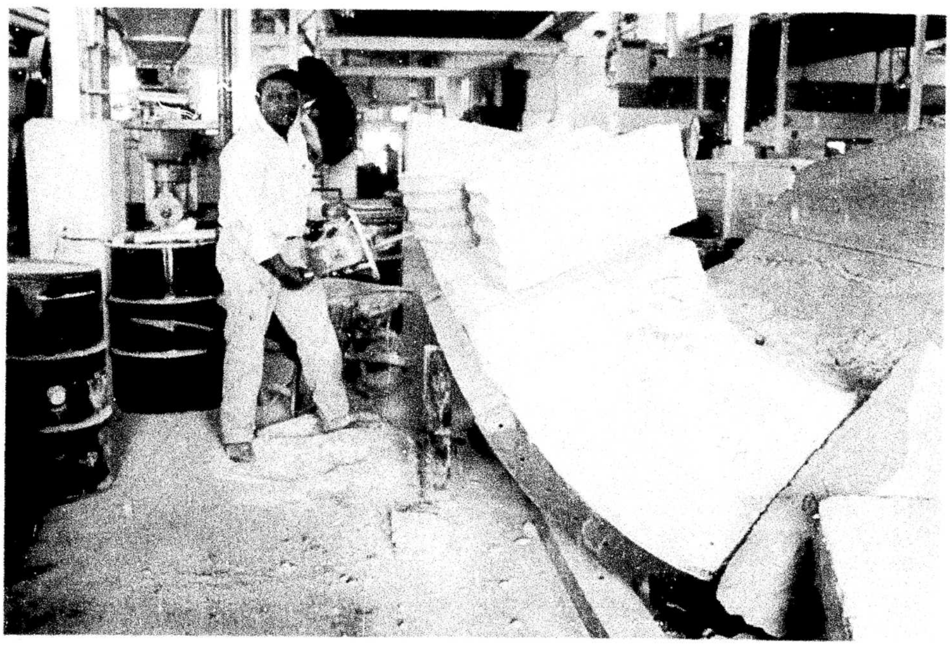


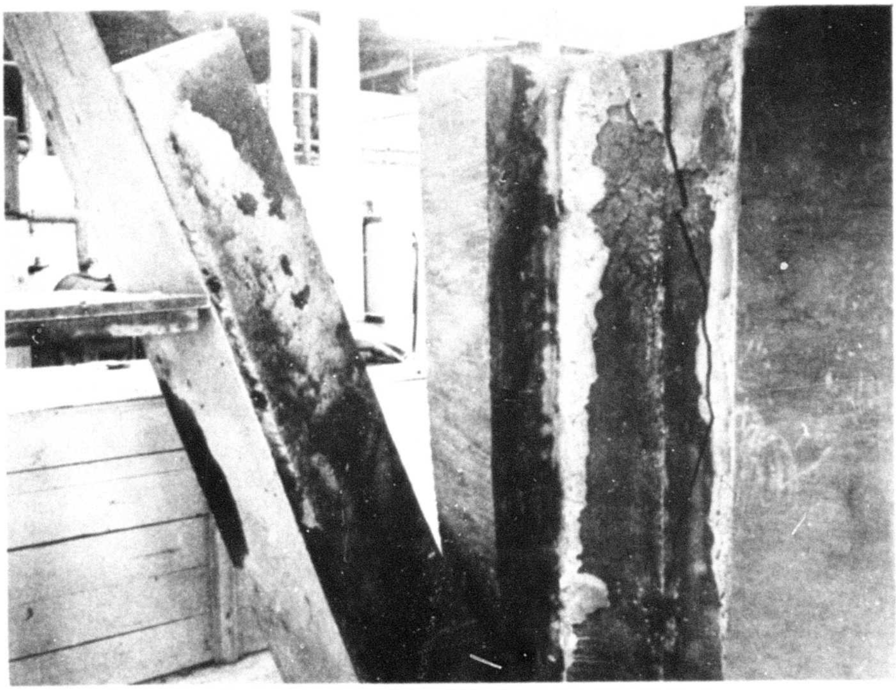
Figure 2.11 Sampling schedule for polystyrene concrete placing operation.

a. Handsawing of cellular concrete.

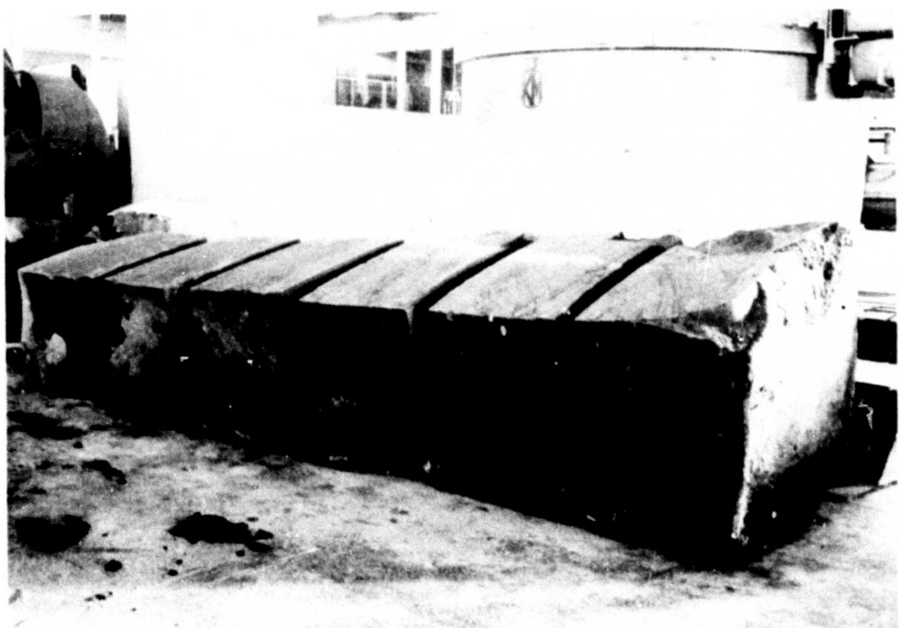


b. Powersawing of polystyrene concrete.

Figure 2.12 Sawing the mass concrete sections into test specimens.



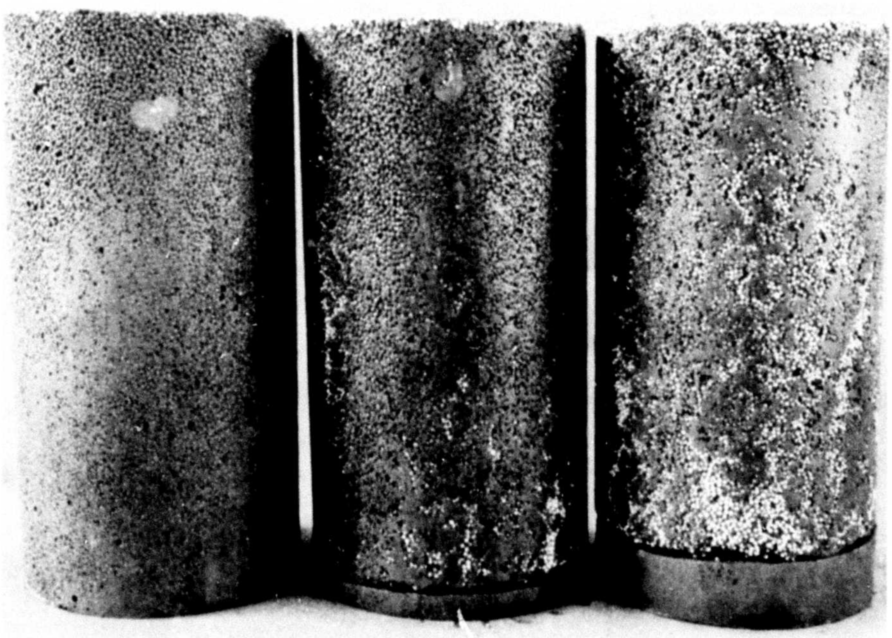
a. Sawed wedge section of cellular concrete.



b. Wedge-shaped blocks of cellular concrete.

Figure 2.13 Wedge sections and blocks of cellular concrete.

a. Finished cubes.



b. Segregated cylinders.

Figure 2.14 Cubes and cylinders of polystyrene concrete.

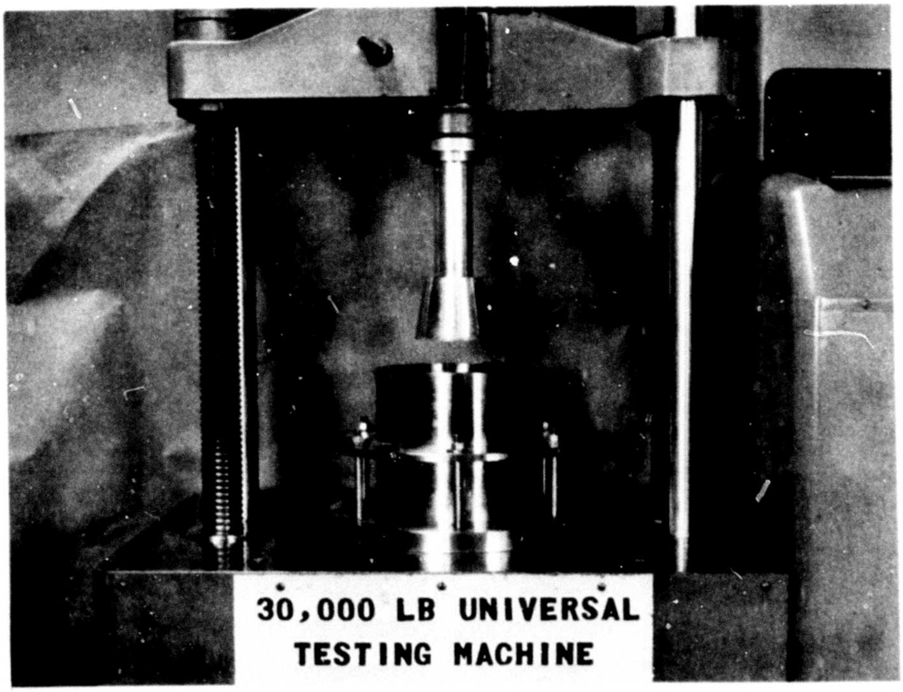
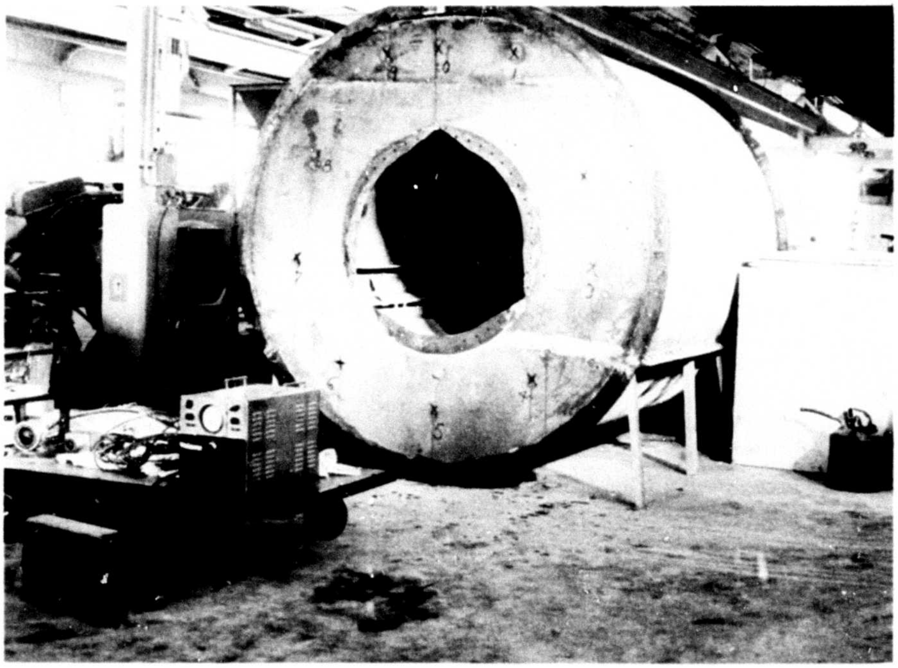
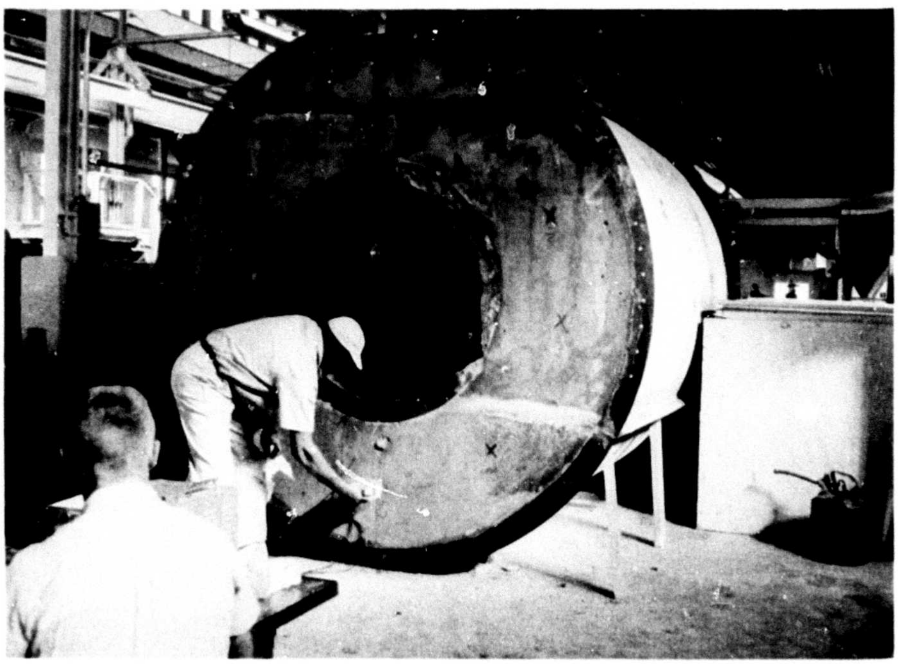


Figure 2.15 Compressive test equipment.



a. Pulse velocity equipment.



b. Performing tests on the cellular concrete section.

Figure 2.16 Ultrasonic pulse velocity test equipment and procedure.

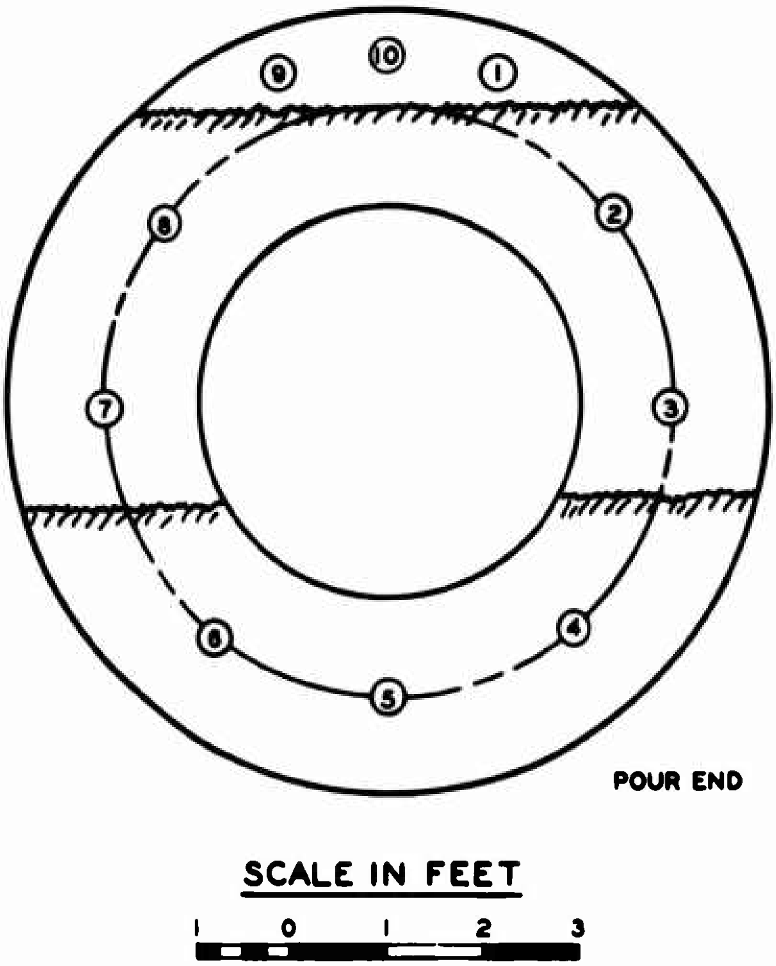


Figure 2.17 Location of points used with soniscope for obtaining ultrasonic pulse velocity of the hardened cellular and vermiculite concrete masses.

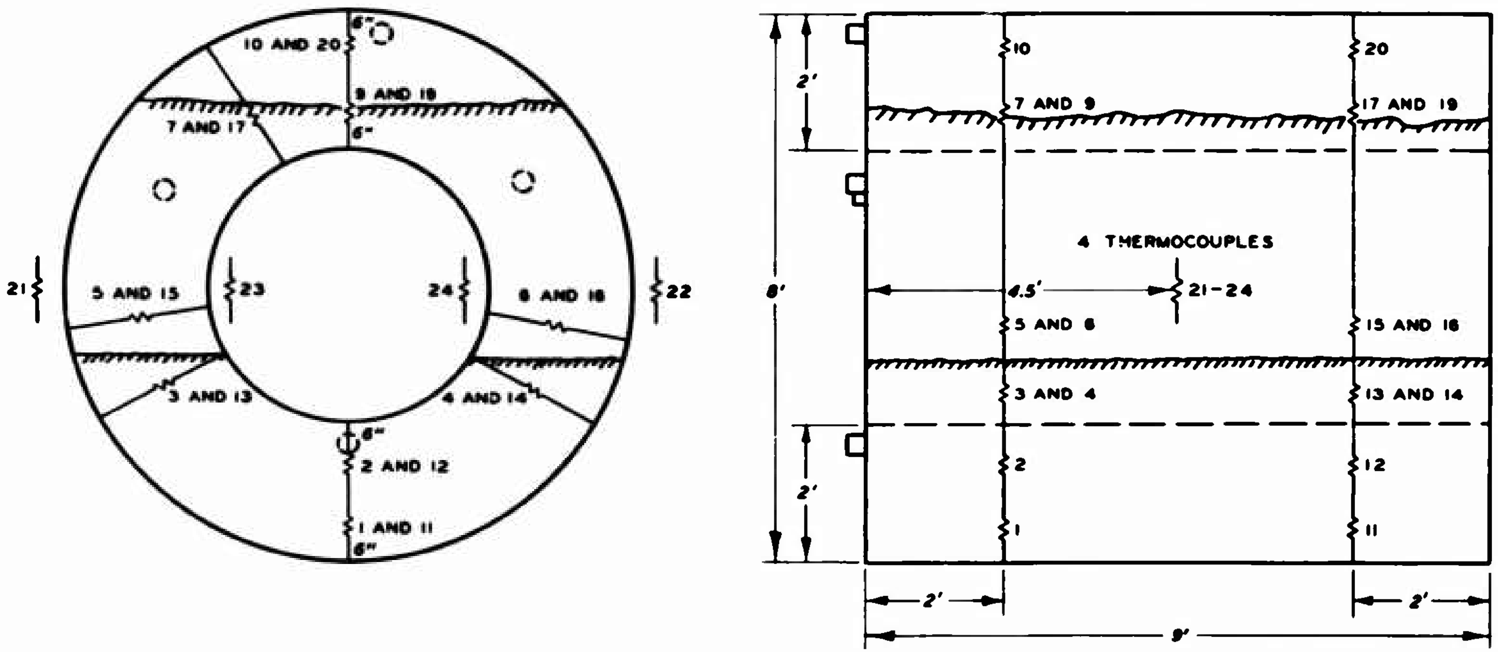


Figure 2.18 Location of thermocouples in cellular concrete placing operation.

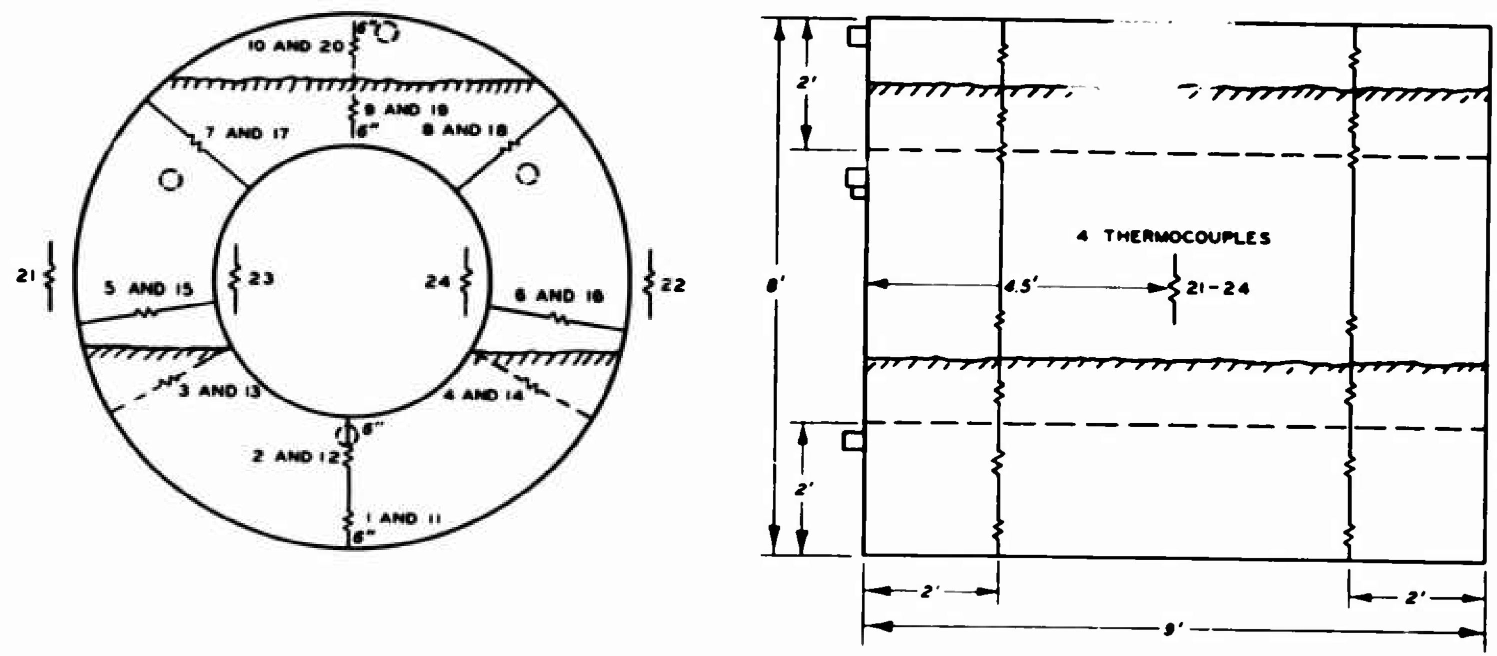


Figure 2.19 Location of thermocouples in vermiculite concrete placing operation.

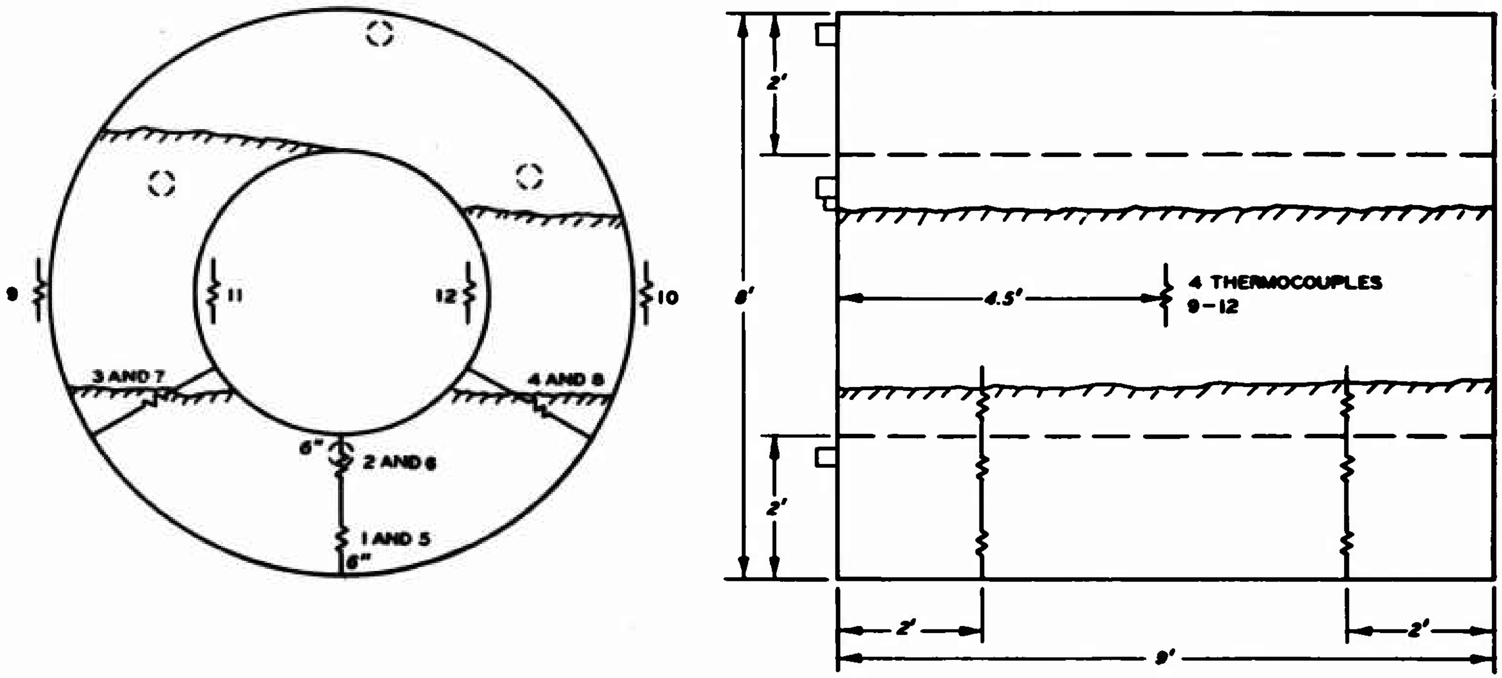


Figure 2.20 Location of thermocouples in polystyrene concrete placing operation.

CHAPTER 3

SUMMARY OF RESULTS

3.1 UNHARDENED AND HARDENED DENSITIES

Unhardened densities (unit weights) were recorded for each batch of concrete made during the four placing operations. Hardened, oven-dry densities were determined from the samples cut in accordance with the sampling schedules (Figures 2.6, 2.7, 2.9, and 2.11) for each of the concrete sections. A summary of the average values of these observations is shown in Tables 3.1 to 3.4 together with some related statistical parameters for (1) each alphabetical slice of material, (2) each numerical series of wedges, (3) each lift, and (4) each entire section. All statistical definitions and procedures used in the determination of the parameters in these tables are in accordance with those contained in Reference 9.

3.1.1 Preliminary Placing Operation. The results of the density analyses for the preliminary placing operation are shown in Table 3.1.

The average unhardened densities for lifts 1 and 2L are almost identical at 33.5 pcf; however, lift 2R varies slightly, being 32.1 pcf. The overall average unhardened density for the 41 batches of concrete made for the entire operation is 33.2 ± 0.4 pcf at the 95 percent confidence interval with samples ranging from 28.8 to 36.0 pcf or a total difference of 7.2 pcf.

Some of the hardened samples taken from the wedge series numbered 2 and 5 included some of the concrete from lifts 1 and 2L and lifts 1 and 2R, respectively, including the joint between these lifts. The cold joints have a tendency to be somewhat denser than other portions of the concrete because the downward bleeding of the excess water in each mixture design carries with it some of the finer cement particles of the batch which are deposited on the top skin of the cold joint, hence increasing the density of the concrete in that area. This is evidenced somewhat by the fact that the oven-dry densities of samples from wedges 2 and 5 are higher than those of most other wedges. The density of wedge 2 is extremely high and is excluded from the following calculations as it is not representative of material in the mass.

The average hardened density for the entire mass (excluding wedge 2) as determined by the 29 oven-dry samples is 21.6 $\pm$ 0.6 pcf at the 95 percent confidence interval. The range of these samples is 19.1 to 24.2 pcf or a total difference of 5.1 pcf. When comparing the hardened density variation with the unhardened density variation, the oven-dry densities appear to be more consistent.

The samples from wedges 3 and 4, which were placed together as lift 1, were combined in Table 3.1 and show an average density for 12 samples of 22.3 $\pm$ 0.7 pcf at the 95 percent confidence interval. Wedge 1, which was lift 2L, had an average density of 20.6 $\pm$ 1.6 pcf,

while wedge 6, which was lift 2R, had an average density of 20.9 ± 1.2 pcf. Both of these values were for six samples at the 95 percent confidence interval.

Using the lifts and corresponding wedges described in the above paragraph, a density loss due to oven-drying of 11.2 pcf was obtained for the first lift. Losses of 12.9 and 11.2 pcf were encountered for lifts 2L and 2R, respectively.

3.1.2 Cellular Concrete. The results of the density analyses for the cellular concrete are shown in Table 3.2.

The average unhardened densities for lifts 1, 2L, 2R, and 3 are 34.0, 34.5, 33.3, and 33.0 pcf, respectively. The overall average unhardened density for the 91 batches of concrete made for the entire operation is 33.8 ± 0.4 pcf at the 95 percent confidence interval with a sample range from 30.4 to 36.0 pcf or a total difference of 5.6 pcf.

The average hardened density for the entire mass as determined by the 46 oven-dry samples is 20.9 ± 0.4 pcf at the 95 percent confidence interval. The range of these samples is 18.6 to 24.6 pcf or a total difference of 6.0 pcf. The total amount of sample variance between the unhardened density samples and the hardened density samples is about the same, being 5.6 and 6.0, respectively.

All the wedge sections that were cut except wedges 5 and 7 contained concrete from two different lifts. In cutting the 8-inch cube

from each wedge block, an attempt was made not to include the cold joints in the sample; however, four of the forty-six cubes cut did include a joint as it was impossible to eliminate the joint completely. All of these cubes were in wedge section 6. Eight cubes were destroyed during the sawing and handling and no density values were recorded.

The hardened density values from wedge sections 4, 5, and 6 were combined in Table 3.2 to represent lift 1. Wedge sections 2 and 3, 7 and 8, and 1 and 9, represent lifts 2L, 2R, and 3, respectively. The average hardened densities for lifts 1, 2L, 2R, and 3 are 21.8 $\pm$ 0.8, 21.4 $\pm$ 0.5, 20.6 $\pm$ 0.8, and 19.9 $\pm$ 0.5 pcf, respectively, at the 95 percent confidence interval. When compared with the unhardened densities for the same lifts, a moisture loss, due to oven-drying and expressed as a density loss, of 12.2, 13.1, 12.7, and 13.1 pcf occurred for lifts 1 through 3, respectively.

<u>3.1.3 Vermiculite Concrete</u>. The results of the density analyses for the vermiculite concrete are shown in Table 3.3.

The average unhardened densities for all lifts are almost identical, varying only 0.9 pcf or from 45.1 to 46.0 pcf. The 86 individual batch densities varied only 3.6 pcf or from 43.6 to 47.2 pcf. The overall average unhardened density for all lifts is 45.7 $\pm$ 0.1 pcf at the 95 percent confidence interval.

The average hardened density for the entire mass as determined

by the 48 oven-dry samples is 22.8 ± 0.8 pcf at the 95 percent confidence interval. The range of these samples is 18.6 to 29.5 pcf or a total difference of 10.9 pcf. When the hardened density variation is compared with the unhardened density variation, the unhardened densities appear to be more consistent.

Wedge sections 1, 3, 6, and 8 contained concrete from two different lifts. In cutting the 8-inch cube from each wedge, an attempt was made not to include the cold joint in the sample; however, in eight cubes the joint was unavoidable.

The hardened density values from wedge sections 4 and 5, 6 and 7, 2 and 3, and 1 and 8 were combined in Table 3.3 to represent lifts 1, 2L, 2R, and 3, respectively. The average hardened densities for lifts 1, 2L, 2R, and 3 are 21.8 ± 0.3, 23.0 ± 1.8, 25.1 ± 2.0, and 21.6 ± 1.6 pcf, respectively, at the 95 percent confidence interval. When compared with the unhardened densities for the same lifts, a moisture loss, due to oven-drying and expressed as a density loss, of 24.1, 22.1, 20.7, and 24.4 pcf occurred for lifts 1, 2L, 2R, and 3, respectively.

3.1.4 Polystyrene Concrete. The results of the density analyses for the polystyrene concrete are shown in Table 3.4.

The average unhardened densities for both lifts are almost the same, varying from 31.2 pcf for lift 1, to 30.8 pcf for lift 2L, and 31.1 pcf for lift 2R. The overall average unhardened density for

all lifts is 31.1 ± 0.4 pcf at the 95 percent confidence interval.

The average hardened density for the entire mass as determined by the 77 oven-dry samples is 20.6 ± 0.8 pcf at the 95 percent confidence interval. The range of these samples is 14.4 to 34.1 pcf or a total difference of 19.7 pcf. When the hardened density variation is compared with the unhardened density variation, the latter appears to be more consistent.

Wedge sections 2 and 6 contained concrete from two different lifts. Twelve of the seventeen cubes from those wedge sections contained cold joints as it was impossible to eliminate them from the cube. Four cubes from the entire section were destroyed during handling.

The hardened density values from wedge sections 3, 4, 5, and 6 were combined in Table 3.4 to represent lift 1. Wedge sections 7, 8, and 9 represent lift 2, and wedge sections 1 and 2 represent lift 3. The average hardened densities for lifts 1, 2L, and 2R are 19.2 ± 0.5, 23.3 ± 1.6, and 19.3 ± 1.1 pcf, respectively, at the 95 percent confidence interval. When compared with the unhardened densities for the same lifts, a moisture loss, due to oven drying and expressed as a density loss, of 12.0, 7.5, and 11.8 pcf occurred for lifts 1, 2L, and 2R, respectively.

3.2 COMPRESSIVE STRENGTH

<u>3.2.1 Cellular Concrete</u>. Eleven moist-cured samples and 13

oven-dried samples were tested at ages from 6 to 28 days. The average value of the average compressive strength to 40 percent deformation of the samples at the various ages is shown in Table 3.5. The individual test observations and the average stresses for a given age are depicted graphically in Figure 3.1. Figure 3.2 shows a typical 28-day stress-deformation curve for a moist-cured and an oven-dried sample.

3.2.2 Vermiculite Concrete. Fifty-five moist-cured samples were tested at ages from 6 to 90 days. Thirteen oven-dried samples were tested at ages from 6 to 28 days. The average values of the average compressive strength to 40 percent deformation at the various ages are shown in Table 3.5. Individual test observations and the average stresses for a given age are depicted graphically in Figure 3.3. Figure 3.4 shows a typical 28-day stress-deformation curve for a moist-cured and an oven-dried sample.

3.2.3 Polystyrene Concrete. Only two cylinders of polystyrene concrete, one from lift 1 and one from lift 2L, were moist-cured and tested at 28 days. The results revealed an average compressive stress at 40 percent deformation of 133 psi for lift 1 and 367 psi for lift 2. Figure 3.5 shows the actual 28-day stress-deformation curves for both of these samples.

3.3 RATE OF HARDENING

Two samples of the cellular concrete used for the cellular

concrete placing operation and two samples of the vermiculite concrete mixture were tested and results are shown in Figure 3.6. Only one sample of each mixture design of the polystyrene concrete was tested; results are shown in Figure 3.6.

3.4 ULTRASONIC PULSE VELOCITIES

Ultrasonic pulse velocities were determined only for the hardened concrete from the cellular and vermiculite concrete placing operations. All the readings on a mass of concrete were made on the same day. As the concrete had been placed in lifts on different days, the age of the concrete in the mass varied from 6 to 14 days.

Data obtained for the cellular concrete mass are shown in Table 3.6. The concrete that was 6 days old represents lift 3, the 10-day concrete represents lifts 2L and 2R, while the 14-day concrete represents lift 1. The wedge section numbers correspond to the actual portion of the concrete through which the pulse was sent. Hardened oven-dry density values for the wedge sections in question are also shown for comparison.

Data obtained for the vermiculite concrete mass are also shown in Table 3.6. The 6-, 9-, and 14-day old concrete corresponds to lifts 3, 2R and 2L, and 1, respectively.

3.5 HEAT DEVELOPMENT

Heat-development measurements were made during all placing

operations except the preliminary placing operation; data are averaged and summarized in Tables 3.7 and 3.8.

The actual temperature-time curves for the cellular concrete lifts are shown in Figure 3.7. The missing portion of the record in Figure 3.7 was caused by malfunctioning recording equipment. Figure 3.8 and Figure 3.9 show the temperature-time curves for the lifts of vermiculite and polystyrene concretes, respectively.

TABLE 3.1 SUMMARY OF DENSITY DETERMINATIONS FOR CONCRETE SECTION OF PRELIMINARY PLACING OPERATION

Item No.	No. of Samples (n)	Density Range	Arithmetic Mean $\pm$ ($\bar{x}$)	Standard Deviation $\pm$ (s)	Standard Deviation of the Mean $\pm$ (s_m)	95 Percent Confidence Interval $\pm$ $t_{0.05}$ s_m
		pcf	pcf	pcf	pcf	pcf
Unhardened:						
Lift 1	21	32.00 36.00	33.54	0.79	0.17	0.36
Lift 2L[a]	10	32.80 34.00	33.48	0.33	0.10	0.24
Lift 2R[a]	10	28.80 34.00	32.08	1.66	0.53	1.19
Entire Mass	41	28.80 36.00	33.17	1.18	0.19	0.37
Hardened:						
Wedge 1 (Lift 2L)	6	19.08 23.34	20.65	1.50	0.61	1.57
Wedge 2	6	23.53 32.11	27.86	2.97	1.21	3.12
Wedge 3	6	20.71 24.04	21.82	1.14	0.47	1.20
Wedge 4	6	20.61 23.64	22.70	1.11	0.45	1.17
Wedge 5	5	19.55 24.15	22.05	2.10	0.94	2.61
Wedge 6 (Lift 2R)	6	19.24 21.54	20.87	1.16	0.47	1.22
Wedge 3 + 4 (Lift 1)	12	20.61 24.04	22.26	1.17	0.34	0.74
Slice A[b]	4	19.64 24.04	21.34	1.89	0.94	3.00
Slice B[b]	5	21.54 23.34	22.32	0.73	0.33	0.90
Slice C[b]	5	19.76 23.87	21.80	1.62	0.73	2.01
Slice D[b]	5	20.35 24.15	21.91	1.81	0.81	2.25
Slice E[b]	5	19.08 23.64	21.38	1.84	0.82	2.28
Slice F[b]	5	19.55 22.87	20.89	1.40	[illegible]	1.74
Entire Mass[b]	29	19.08 24.15	21.60	1.57	0.29	0.60

[a] L indicates left; R indicates right.
[b] Excluding wedge 2.

TABLE 3.2 SUMMARY OF CELLULAR CONCRETE DENSITY DETERMINATIONS

Item No.	No. of Samples (n)	Density Range	Arithmetic Mean $\pm$ ($\bar{x}$)	Standard Deviation $\pm$ (s)	Standard Deviation of the Mean $\pm$ (s_m)	95 Percent Confidence Interval $\pm t_{0.95} s_m$
		pcf	pcf	pcf	pcf	pcf
Unhardened:						
Lift 1	38	31.60 36.00	33.95	0.94	0.15	0.31
Lift 2L[a]	21	33.20 36.00	34.46	0.83	0.18	0.38
Lift 2R[a]	21	30.40 36.00	33.31	1.39	0.30	0.63
Lift 3	11	32.00 34.00	32.98	0.65	0.20	0.44
Entire Mass	91	30.40 36.00	33.80	1.11	0.12	0.40
Hardened:						
Wedge 1	6	19.35 21.10	20.24	0.69	0.28	0.72
Wedge 2	5	20.45 21.72	20.83	0.52	0.23	0.64
Wedge 3	5	21.58 22.39	21.89	0.35	0.16	0.44
Wedge 4	5	19.86 21.62	20.88	0.67	0.30	0.83
Wedge 5	4	20.95 21.86	21.46	0.38	0.19	0.60
Wedge 6	5	21.26 24.56	23.35	1.48	0.74	2.36
Wedge 7	6	20.11 22.16	21.33	0.88	0.36	0.92

(Continued)

[a] L indicates left; R indicates right.

TABLE 3.2 (CONCLUDED)

Item No.	No. of Samples (n)	Density Range	Arithmetic Mean $\pm$ ($\bar{x}$)	Standard Deviation $\pm$ (s)	Standard Deviation of the Mean $\pm$ (s_m)	95 Percent Confidence Interval $\pm$ $t_{0.95}$ s_n
		pcf	pcf	pcf	pcf	pcf
Hardened (Continued):						
Wedge 8	5	18.60 21.00	19.77	0.89	0.40	1.10
Wedge 9	6	18.57 20.41	19.63	0.75	0.31	0.79
Wedge 4 + 5 + 6 (Lift 1)	13	19.86 24.56	21.82	1.39	0.38	0.84
Wedge 7 + 8 (Lift 2R)	11	18.60 22.16	20.62	1.17	0.35	0.78
Wedge 2 + 3 (Lift 2L)	10	20.45 22.39	21.36	0.70	0.22	0.50
Wedge 1 + 9 (Lift 3)	12	18.57 21.10	19.93	0.76	0.22	0.48
Slice A	9	18.57 22.08	20.67	1.29	0.43	0.99
Slice B	9	18.94 24.56	21.08	1.54	0.51	1.18
Slice C	9	19.54 21.85	20.59	0.92	0.35	0.85
Slice D	9	19.94 21.86	20.80	0.70	0.31	0.87
Slice E	9	19.86 23.31	21.25	1.13	0.38	0.87
Slice F	9	18.60 24.26	21.26	1.78	0.67	1.65
Entire Mass	46	18.57 24.56	20.94	1.27	0.19	0.38

TABLE 3.3 SUMMARY OF VERMICULITE CONCRETE DENSITY DETERMINATIONS

Item No.	No. of Samples (n)	Density Range	Arithmetic Mean $\pm$ ($\bar{x}$)	Standard Deviation $\pm$ (s)	Standard Deviation of the Mean $\pm$ (s_m)	95 Percent Confidence Interval $\pm t_{0.95} s_m$
		pcf	pcf	pcf	pcf	pcf
Unhardened:						
Lift 1	32	44.6 47.2	45.91	0.63	0.11	0.22
Lift 2	20	43.6 46.0	45.12	0.58	0.13	0.25
Lift 3	22	45.2 46.2	45.81	0.28	0.06	0.12
Lift 4	12	44.8 47.2	45.97	0.84	0.24	0.54
Entire Mass	86	43.6 47.2	45.71	0.66	0.07	0.14
Hardened:						
Wedge 1	6	18.64 21.90	20.25	1.10	0.45	1.16
Wedge 2	6	21.41 29.51	24.20	3.47	1.41	3.64
Wedge 3	6	21.16 28.87	25.98	2.81	1.15	2.95
Wedge 4	6	21.35 22.85	22.04	0.55	0.22	0.58
Wedge 5	6	20.74 21.96	21.46	0.55	0.23	0.58
Wedge 6	6	19.50 23.41	21.22	1.43	0.59	1.51
Wedge 7	6	21.91 28.54	24.81	2.98	1.22	3.13
Wedge 8	6	20.36 25.30	22.51	2.01	0.82	2.11

(Continued)

TABLE 3.3 (CONCLUDED)

Item No.	No. of Samples (n)	Density Range	Arithmetic Mean $\pm$ ($\bar{x}$)	Standard Deviation $\pm$ (s)	Standard Deviation of the Mean $\pm$ (s_m)	95 Percent Confidence Interval $\pm t_{0.95} s_m$
		pcf	pcf	pcf	pcf	pcf
Hardened (Continued):						
Wedge 4 + 5 (Lift 1)	12	20.74 21.96	21.75	0.51	0.15	0.32
Wedge 6 + 7 (Lift 2L[a])	12	19.50 28.54	23.01	2.90	0.84	1.84
Wedge 2 + 3 (Lift 2R[a])	12	21.16 29.51	25.09	3.15	0.91	2.00
Wedge 1 + 8 (Lift 3)	12	18.64 23.77	21.58	1.89	0.74	1.62
Slice A	8	19.50 29.51	24.35	4.02	1.42	3.66
Slice B	8	21.20 28.18	24.62	2.87	1.02	2.61
Slice C	8	18.64 27.51	22.42	2.77	0.98	2.52
Slice D	8	20.23 24.25	22.13	1.35	0.48	1.23
Slice E	8	19.55 26.64	21.82	2.12	0.75	1.93
Slice F	8	20.41 22.53	21.25	0.74	0.26	0.67
Entire Mass	48	18.64 29.51	22.78	2.73	0.39	0.79

[a] L indicates left; R indicates right.

TABLE 3.4 SUMMARY OF POLYSTYRENE CONCRETE DENSITY DETERMINATIONS

Item No.	No. of Samples (n)	Density Range	Arithmetic Mean $\pm$ ($\bar{x}$)	Standard Deviation $\pm$ (s)	Standard Deviation of the Mean $\pm$ (s_m)	95 Percent Confidence Interval $\pm t_{0.95} s_m$
		pcf	pcf	pcf	pcf	pcf
Unhardened:						
Lift 1	28	27.2 34.8	31.2	2.20	0.42	0.85
Lift 2L[a]	15	29.2 32.0	30.8	0.87	0.22	0.47
Lift 2R[a]	12	30.8 31.6	31.1	0.23	0.07	0.15
Entire Mass	55	27.2 34.8	31.1	1.64	0.22	0.45
Hardened:						
Wedge 1	9	20.36 21.65	20.90	0.38	0.13	0.30
Wedge 2	8	14.45 19.87	17.41	1.93	0.68	1.61
Wedge 3	9	18.03 19.24	18.61	0.41	0.14	0.32
Wedge 4	8	17.32 20.55	19.14	0.99	0.35	0.83
Wedge 5	8	17.31 22.35	19.27	1.46	0.52	1.23
Wedge 6	9	15.81 22.59	19.92	2.04	0.68	1.57
Wedge 7	9	24.76 34.14	27.89	2.98	0.99	2.28
Wedge 8	9	20.19 21.78	20.86	0.64	0.21	0.48
Wedge 9	8	15.02 23.81	21.03	2.74	0.97	2.29

(Continued)

[a] L indicates left; R indicates right.

TABLE 3.4 (CONCLUDED)

Item No.	No. of Samples (n)	Density Range	Arithmetic Mean $\pm$ ($\bar{x}$)	Standard Deviation $\pm$ (s)	Standard Deviation of the Mean $\pm$ (s_m)	95 Percent Confidence Interval $\pm$ $t_{0.95}$ s_m
		pcf	pcf	pcf	pcf	pcf
Hardened (Continued):						
Wedge 3 + 4 + 5 + 6	34	15.81 22.59	19.24	1.40	0.24	0.49
Wedge 7 + 8 + 9	26	15.02 34.14	23.34	4.00	0.78	1.62
Wedge 1 + 2	17	14.45 21.65	19.26	2.22	0.54	1.14
Slice A	9	15.81 34.14	20.78	5.56	1.85	4.27
Slice B	8	18.33 25.55	20.57	2.39	0.84	1.99
Slice C	9	17.13 29.26	20.55	3.56	1.18	2.72
Slice D	9	16.17 25.19	20.26	2.79	0.93	2.14
Slice E	9	14.45 29.87	20.68	4.10	1.37	3.16
Slice F	9	15.55 28.39	20.66	3.45	1.15	2.65
Slice G	7	18.73 26.03	21.12	2.46	0.93	2.14
Slice H	9	15.02 27.79	20.50	3.46	1.16	2.67
Slice J	8	18.42 24.76	20.62	1.94	0.68	1.61
Entire Mass	77	14.45 34.14	20.63	3.37	0.38	0.76

TABLE 3.5 RESULTS OF COMPRESSIVE STRENGTH TESTS OF CELLULAR AND VERMICULITE CONCRETE

Age	Moist-Cured Samples		Oven-Dried Samples	
	No. of Samples	Average Compressive Stress to 40 Percent Deformation	No. of Samples	Average Compressive Stress to 40 Percent Deformation
days		psi		psi
Cellular Concrete:				
6	3	47	3	72
10	3	60	3	112
14	3	78	3	129
28	2	84	4	122
Vermiculite Concrete:				
6	3	107	3	147
9	3	113	3	181
14	3	121	4	199
20	4	132	--	--
23	4	138	--	--
28	2	144	3	235
60	18	160	--	--
90	18	161	--	--

TABLE 3.6 ULTRASONIC PULSE VELOCITIES FOR CELLULAR AND VERMICULITE CONCRETE

Position No.[a]	Wedge Section No.	Age	Velocity	Average Oven-Dry Density
		days	ft/sec	pcf
Cellular Concrete:				
1	1	6	4,305	20.24
9	9	6	3,695	19.63
10	1	6	3,035	20.24
2	2	10	5,055	20.83
3	3	10	4,640	21.89
7	7	10	5,235	21.33
8	8	10	5,215	19.77
4	4	14	6,430	20.88
5	5	14	6,205	21.46
6	6	14	4,120	23.35
Vermiculite Concrete:				
1	1	6	2,616	20.25
9	8	6	3,249	22.31
10	1	6	3,308	20.25
2	2	9	1,662	24.20
3	3	9	3,249	25.98
7	6	9	2,356	24.81
8	7	9	2,416	22.31
4	4	14	2,341	22.04
5	4	14	2,483	21.46
6	5	14	2,403	21.22

[a] Attempts to obtain pulse velocities along the cold joints were unsuccessful. A reading of 7,200 ft/sec was obtained, however, from a position 2 inches above the cold joint in wedge section 6 of the cellular concrete. Positions are shown in Figure 2.17.

TABLE 3.7 SUMMARY OF CELLULAR AND VERMICULITE CONCRETE PLACING TEMPERATURE AND DENSITY DATA

Lift No.	Average Maximum Temperature	Average Unit Weight	Average Oven-Dry Density
	°F	pcf	pcf
Cellular Concrete:			
1	154	33.95	21.82
2R[a]	160+	33.21	20.62
2L[a]	160+	34.46	21.36
3	149	32.98	19.93
Vermiculite Concrete:			
1	99	45.91	21.75
2L	109	45.12	23.01
2R	109	45.81	25.09
3	101	45.71	21.58

[a] R indicates right; L indicates left.

TABLE 3.8 SUMMARY OF POLYSTYRENE CONCRETE PLACING TEMPERATURE DATA

Thermocouple No.	Location	Maximum Temperature °F
1	Bottom, front	161
2	Center, front	150
3	Top, front	137
4	Top, front	142
5	Bottom, rear	161
6	Center, rear	136
7	Top, rear	94
8	Top, rear	121

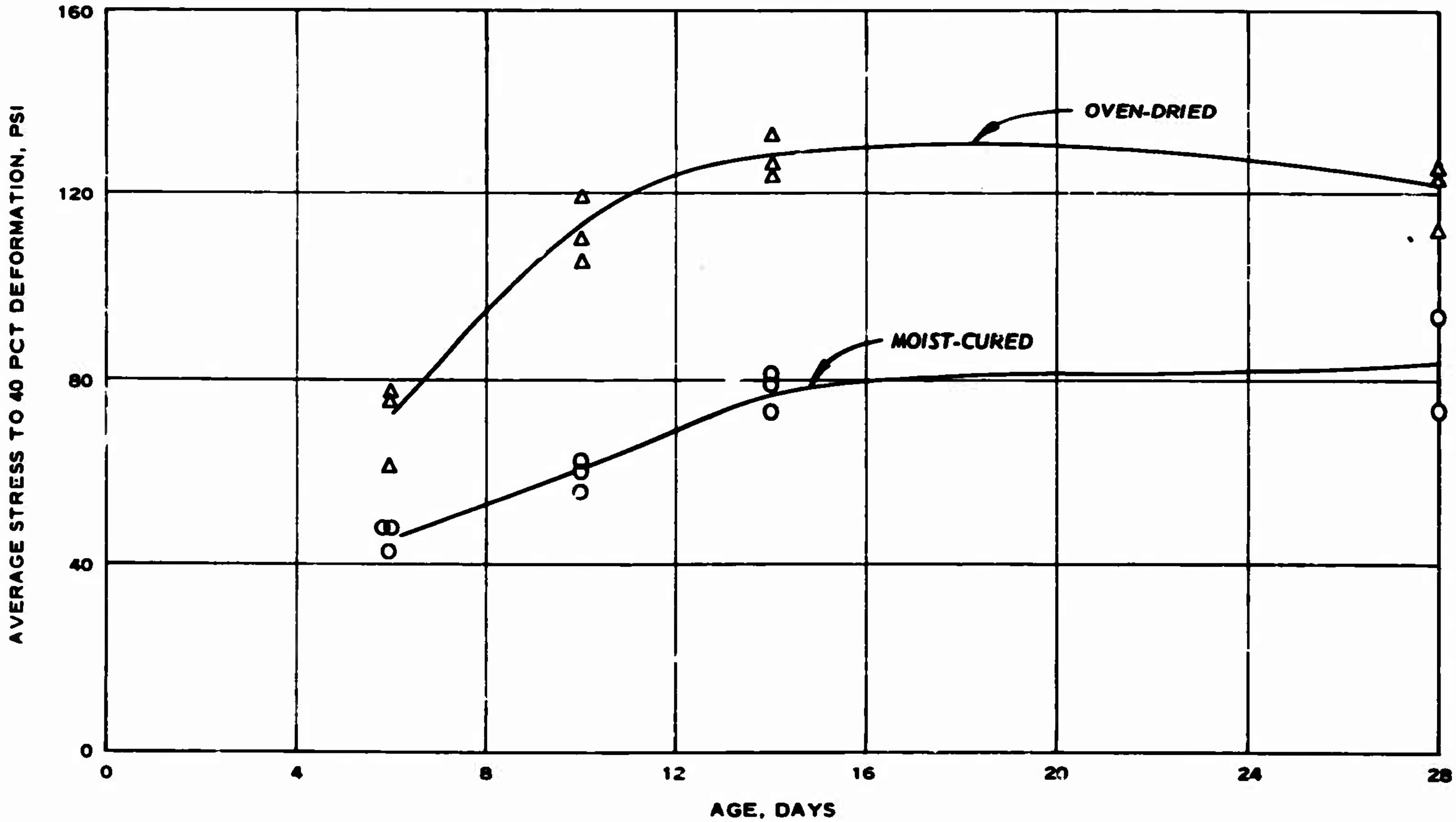


Figure 3.1 Average stress versus age relation for cellular concrete.

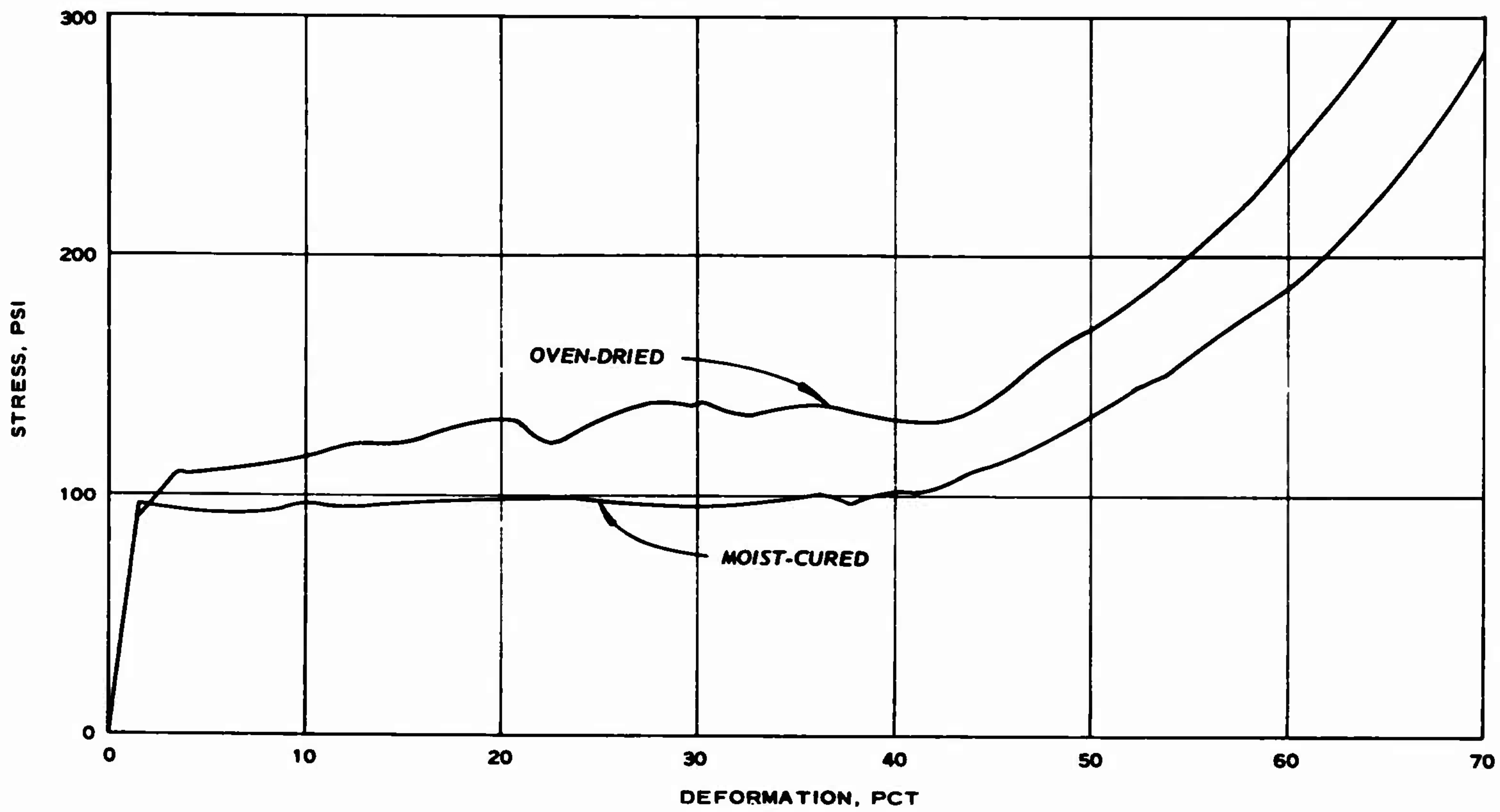


Figure 3.2 Typical stress-deformation curves for cellular concrete.

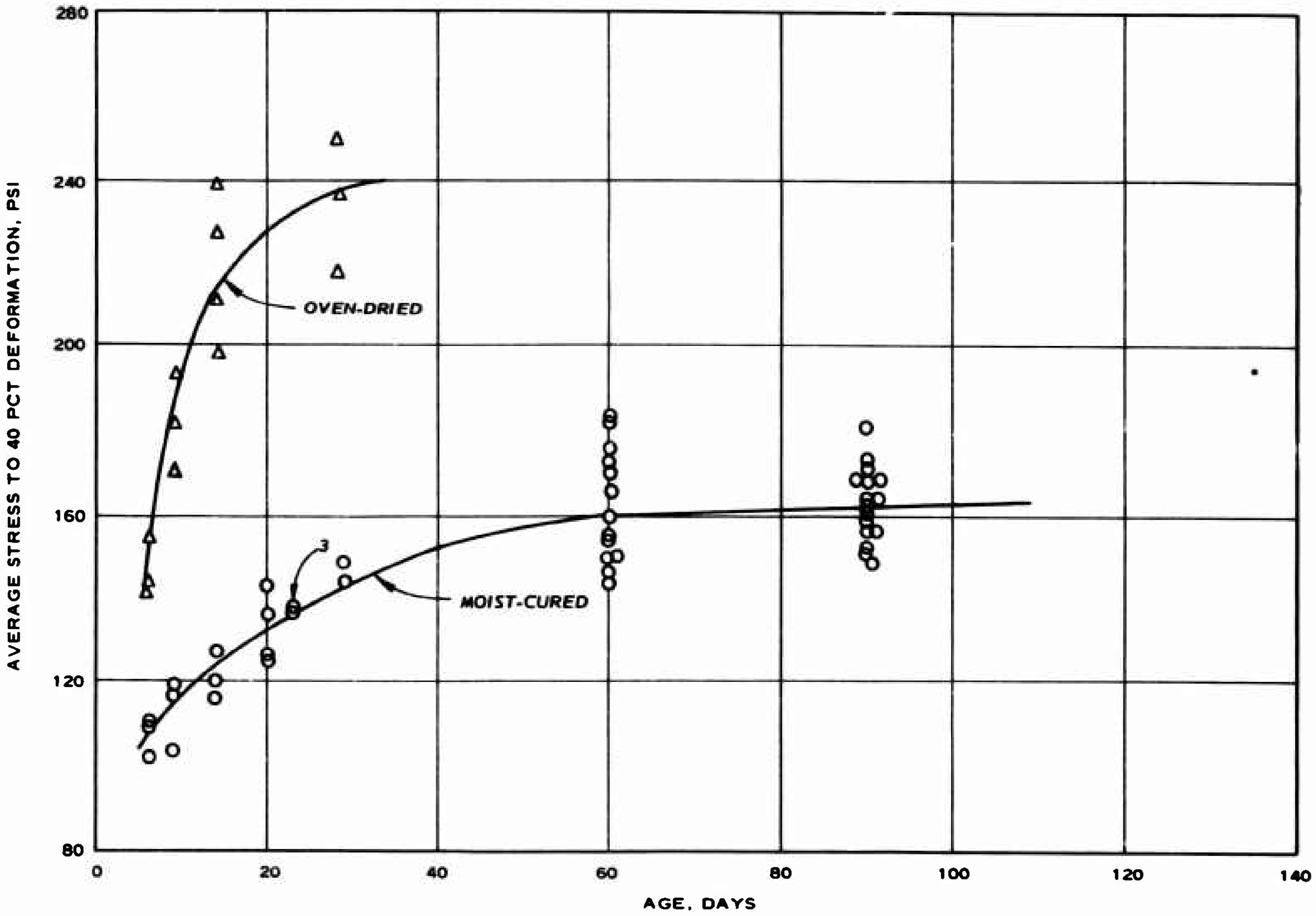


Figure 3.3 Average stress versus age relation for vermiculite concrete.

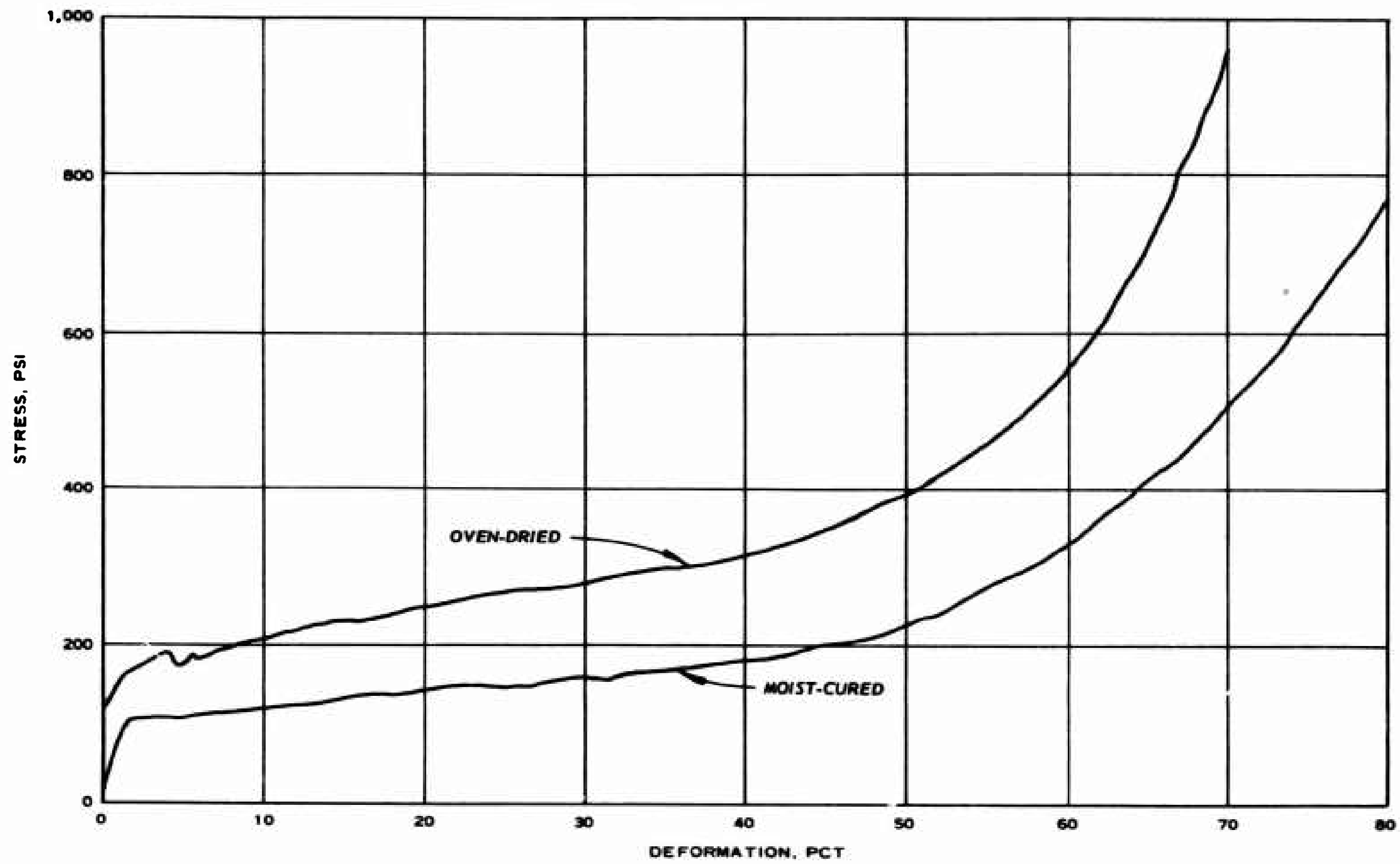


Figure 3.4 Typical stress-deformation curves for vermiculite concrete.

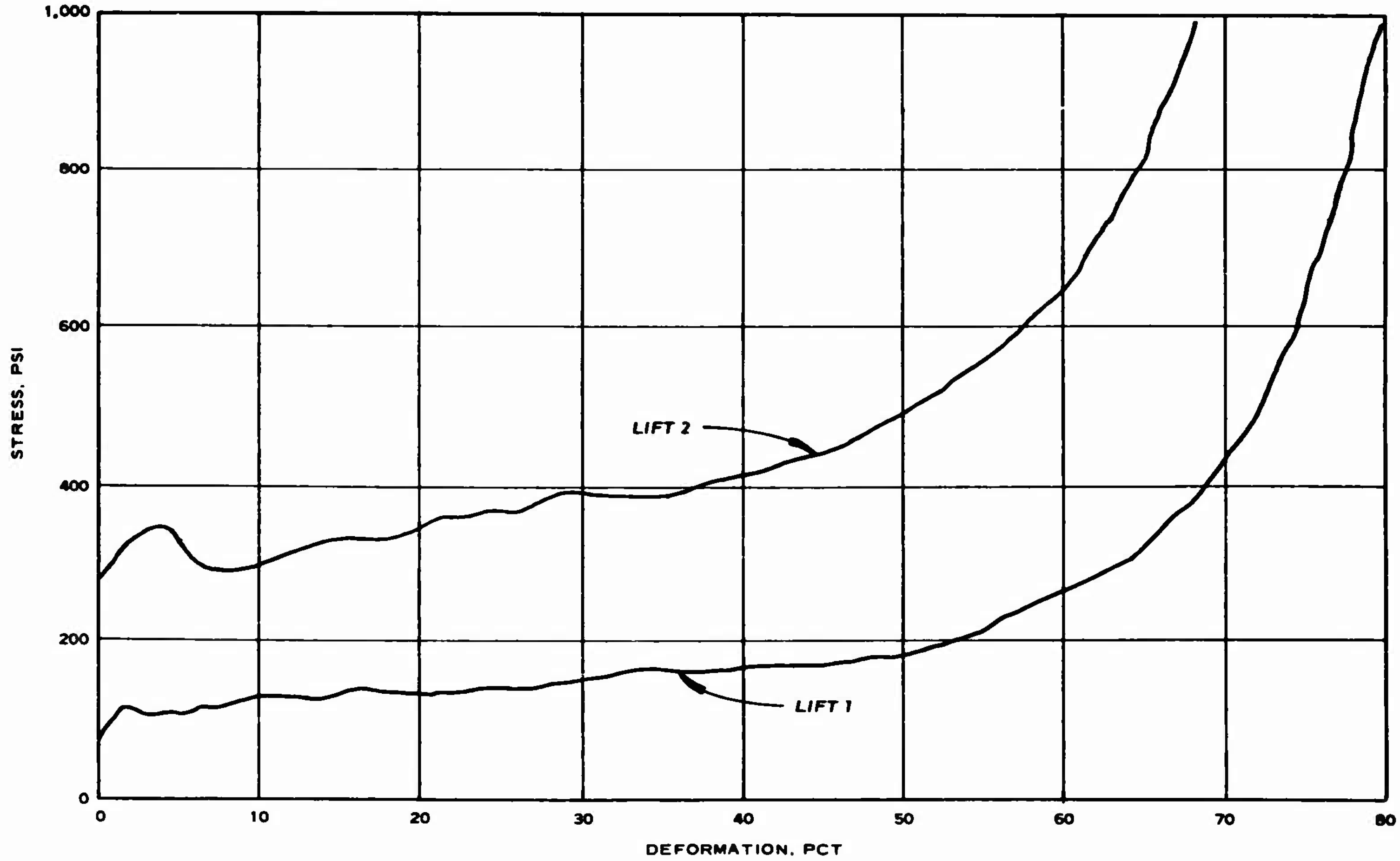


Figure 3.5 Typical one-dimensional static stress-deformation curves for polystyrene concrete.

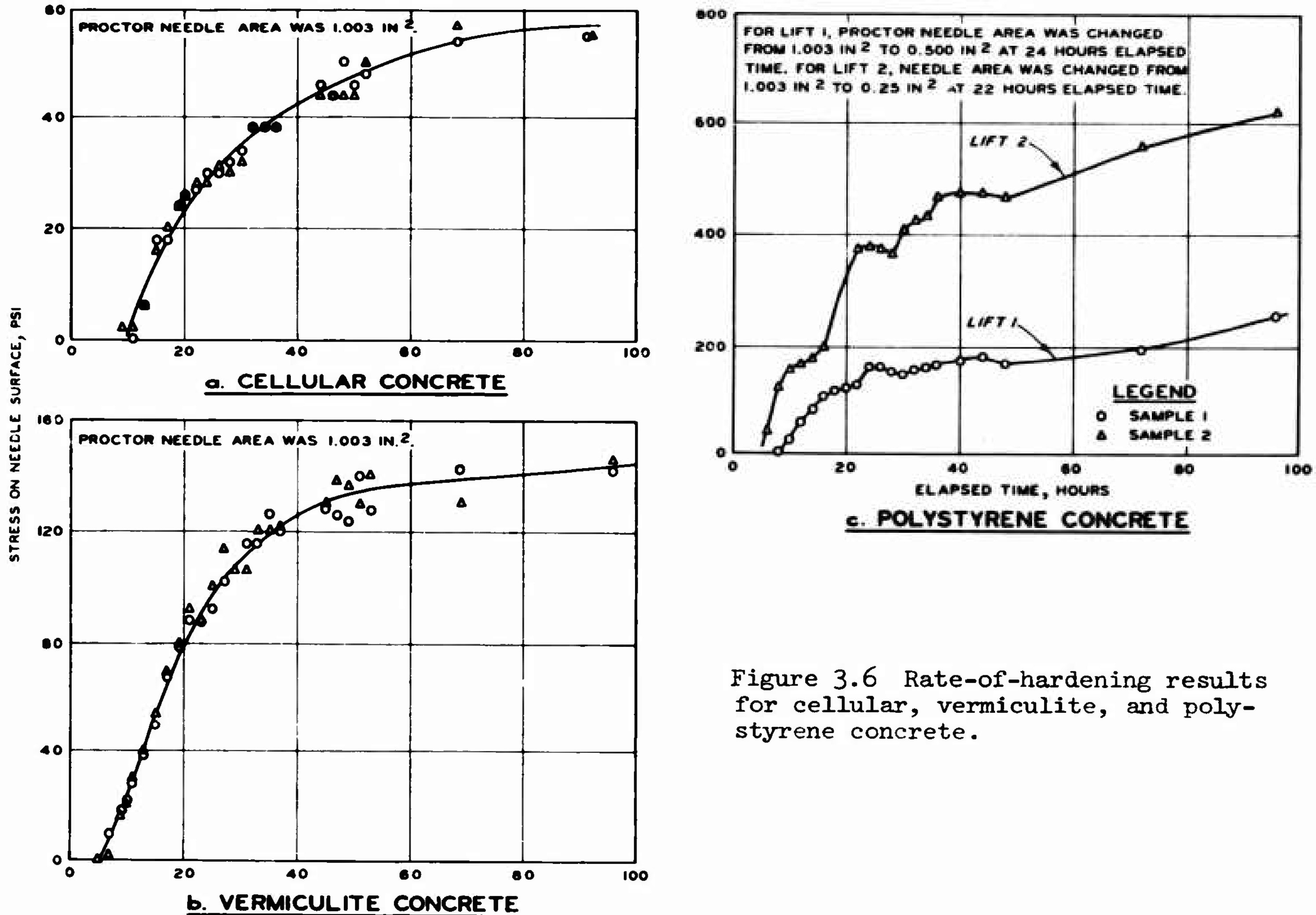


Figure 3.6 Rate-of-hardening results for cellular, vermiculite, and polystyrene concrete.

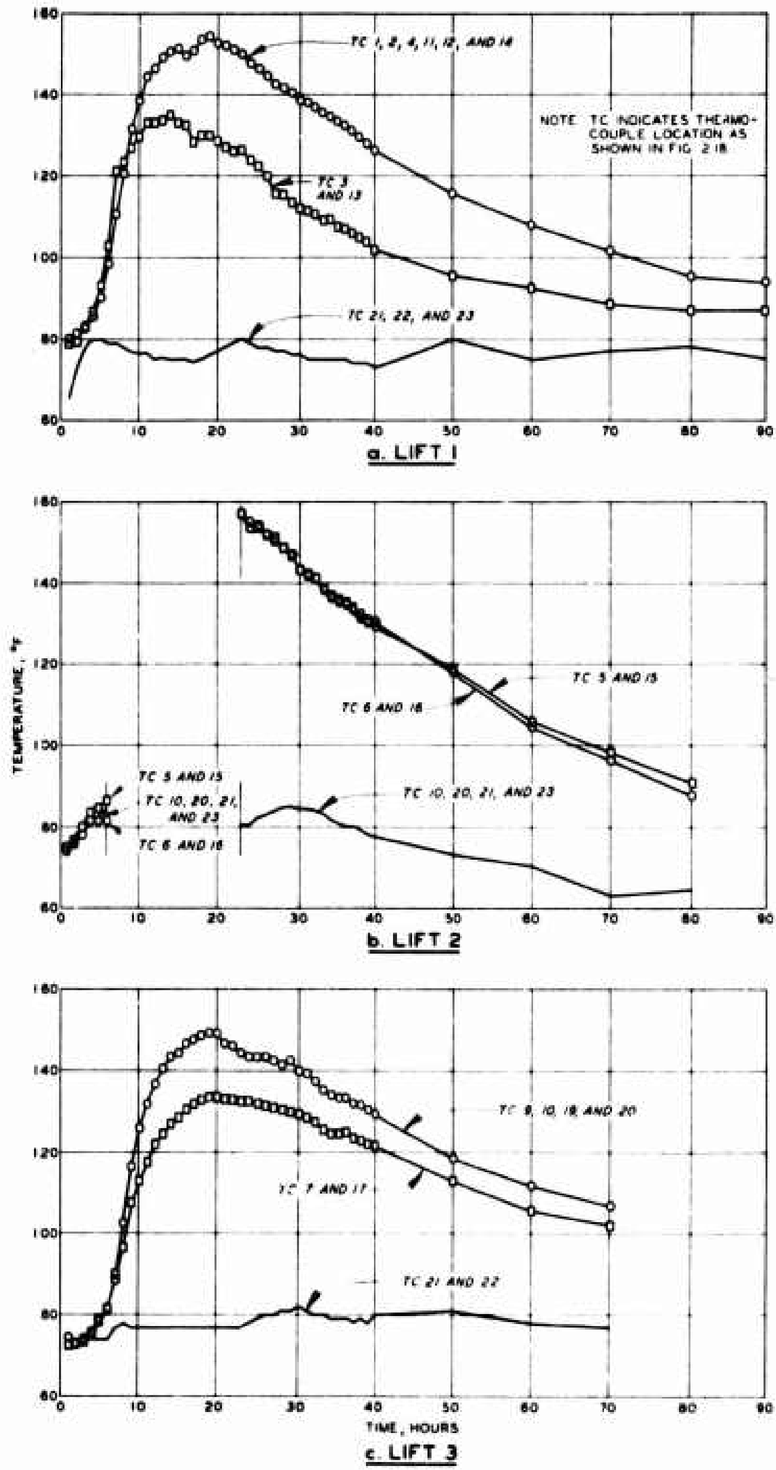
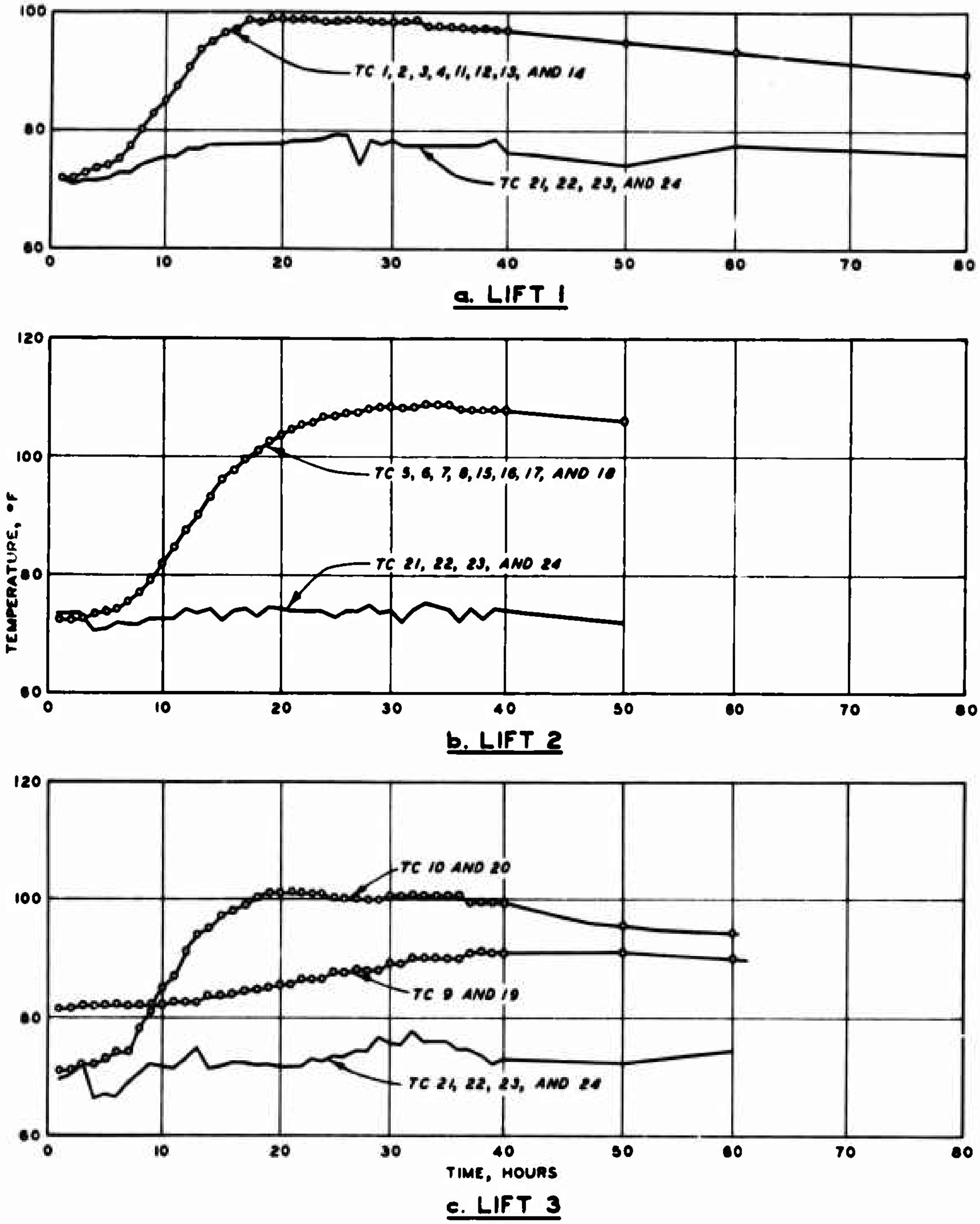


Figure 3.7 Heat-development curves for lifts 1, 2, and 3 of cellular concrete.



NOTE: TC INDICATES THERMOCOUPLE
LOCATION AS SHOWN IN FIGURE 2.19.

Figure 3.8 Heat-development curves for lifts 1, 2, and 3 of vermiculite concrete placing operation.

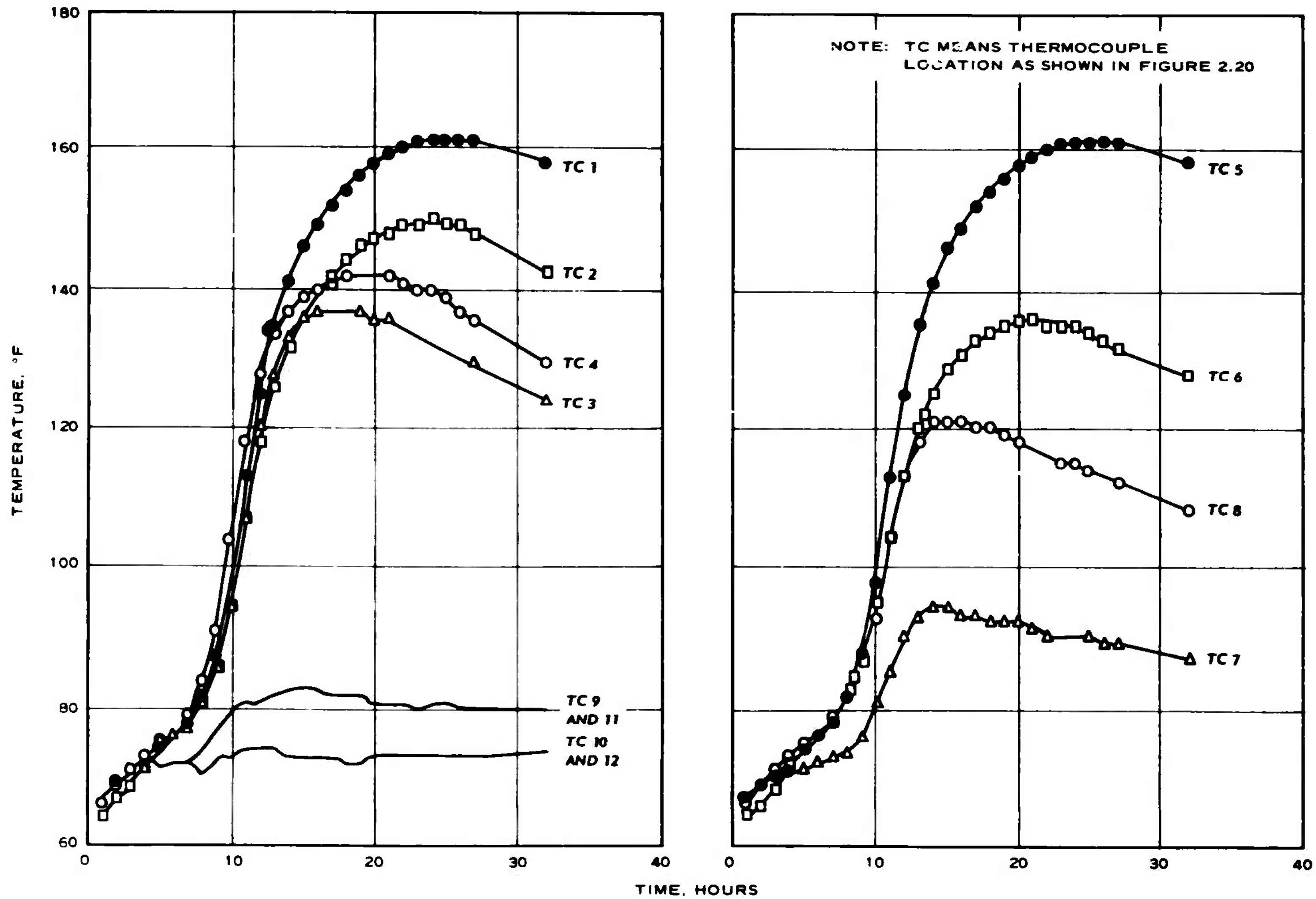


Figure 3.9 Heat-development curves for polystyrene concrete placing operation.

CHAPTER 4

DISCUSSION OF RESULTS

4.1 SOME CONSIDERATIONS PERTAINING TO HANDLING, BATCHING, AND PLACING BACKPACKING CONCRETES

The handling and batching of the cellular concrete were relatively uncomplicated as only cement, water, and preformed foam composed the ingredients. The vermiculite and polystyrene concrete did not use a preformed foam for air content but used a neutralized vinsol resin (NVR) solution instead; they also required the loose volume proportioning of the low-density vermiculite and polystyrene aggregates.

Because aggregate in bulk is not needed for cellular concrete, the aggregate storage and handling problems associated with the use of low-density aggregate concretes do not exist. Some storage and handling of the containers of the foaming agent concentrate are necessary, but a standard 55-gallon drum of foaming agent concentrate may produce enough stable foam for 200 yd^3 of cellular concrete, depending on the desired density of the concrete. The storage and handling of 55-gallon drums are minimal compared with that of almost 200 yd^3 of the bulk aggregate required to produce 200 yd^3 of low-density aggregate concrete. The expansion and grading of low-density aggregates can be done on the jobsite if desired. By shipping the raw material from which the low-density aggregates are

made directly to the jobsite and establishing an expanding and processing plant on the jobsite, the problems of shipping the bulky expanded aggregate would be minimized and shipping costs reduced. This approach would be practical only for large amounts of aggregate.

Because of the high air content of cellular concrete, it normally cannot be batched, handled, and transported for long distances in bulk form to the site where it will be used without substantial losses in air content. The low-density aggregate concretes have much lower air contents, however, and are therefore more suitable for handling and transporting for long distances in bulk form than cellular concrete.

During the program, unit weight of the freshly mixed concrete at the mixer was used as a quality control device. With some development work for a given mixture proportion, the density can be related to the strength of the concrete (Reference 3). The principal cause of density changes from batch to batch of the freshly mixed concrete, assuming that the amounts of water, cement, and aggregate (if used) are held constant, is the air content. For the operations reported in this study, variations in the air content of the cellular concrete can be attributed to human errors during the addition of the timed foam and to changes in air content during mixing and pumping. For prototype operations, the human error can be eliminated by replacing the stopwatch timing procedure with a

reset electric timer and solenoid valves for repetitive foam cycle discharge. The variations occurring during mixing and placing will depend on the equipment used, the speed at which it is operated, the type of discharge hose used, the length of hose and amount of hose couplings in that length, and the differential pumping heads involved. These variations will have to be determined on the job and compensated for accordingly as they occur.

For air entrainment, the vermiculite and polystyrene concrete utilized an NVR solution added to the mixing water and depended on the mixing action to froth the solution and produce air bubbles suitable for entrainment in the concrete. The amount of air entrainment developed by the NVR is affected by temperature, mixing action, and mixing duration; if these factors are not adequately controlled, some problems of batch-to-batch reproducibility may occur. To eliminate this potential problem area, the preformed foam used in the cellular concrete could be used to provide the desired air content. This technique is often used in the roof-deck insulation industry which uses both cellular and low-density aggregate concretes as insulation fill. The same causes of variation in density during mixing and placing discussed for the cellular concrete also apply to the low-density aggregate concrete, plus one additional factor. This factor is the high porosity of the aggregates that are used which makes the aggregates susceptible of some

collapse and consolidation during batching and placing, hence increasing the density. All these factors must be compensated for on the job, however, for actual conditions of batching and placing.

The density control during this program was conducted at the mixer because of the inaccessibility of the bulkhead end of the discharge hose. In the prototype, the density control should be at the point of placement of the concrete so that any variations occurring during pumping can be determined. To ensure that a reliable degree of reproducibility is achieved at the mixer, a constant-speed horizontal drum mixer should be used since it appears to be best suited for this type of concrete batching. Periodic unit weight checks can be made at the mixer to determine batch reproducibility. These checks, when compared with the checks made at the point of placement, will indicate the amount of variation caused during pumping and will be useful in optimizing mixing and pumping speeds, type and length of hose, and the maximum heads against which the concrete can be pumped.

The ranges and amounts of variation in the unhardened density checks made for each placing operation in this program (Tables 3.1 to 3.4) are greater than would be desirable in prototype sections. The elimination of most of the human error and equipment variations can be achieved by use of larger, more sophisticated types of batching and placing equipment for the prototype situation. The

use of more sophisticated equipment should greatly improve the batch-to-batch reproducibility and thus reduce the range and variations of the densities and, hence, of the concrete strengths.

Density ranges and variations in the samples of low-density aggregate concretes taken at the mixer are smaller than those of the cellular concrete (see Tables 3.1 to 3.4). This bears out the assumption that variations in air content due to human error may be significant because the desired quantity of air for the cellular concrete was added directly to the cement slurry as foam by laboratory personnel while in the low-density aggregate concrete, the air content developed was determined by the amount of accurately measured NVR in the batch and the mixing speed and duration, which were kept constant. The hardened density ranges and variations of the cellular and low-density aggregate concretes were exactly opposite from the unhardened densities, however, with the cellular concrete having a smaller range and variation. This indicates that some segregation occurs in the low-density aggregate concrete between the mixer and the in-place concrete. The cellular concrete, having no aggregate, does not appear to change significantly with respect to density range and variation from the mixer to the in-place concrete; however, some gross but uniform density change may have occurred that was not discernible because of the procedures of measuring wet unit weights and dry weights of hardened samples. The segregation of

the vermiculite concrete can be seen in Figure 4.1, while the segregation of the polystyrene concrete is vividly depicted in Figures 4.2 and 4.3. Whether or not the segregation occurred during pumping or while the material was flowing from the front to the rear of the form could not be distinctly determined. Based on the observation of the polystyrene concrete mass, it is suspected that in this case most of the segregation occurred after the concrete left the discharge hose. It should not be concluded from these observations that segregation in low-density aggregate concretes is unavoidable. The optimization of the mixture proportions with respect to the pumpability of the concrete and a study of the pumping characteristics of the concrete would probably eliminate most if not all of the segregation problems.

Once in the formwork, some downward bleeding of the excess mixture water in the concrete occurred. Most of this water leaked out of the bottom of the form at the lap joints of the corrugated sections. In the prototype this water might not be able to escape from the system, thus forming a small zone of weaker backpacking concrete at the bottom of the section due to the increased water content in that area. In all probability, the weaker zone will contain only the amounts of excess mixture water that can bleed down during the casting of the lower portions of the lift forming the invert of the section and will be very small in both vertical and lateral extent.

This may not be a problem from the standpoint of the design of the structural liner; but if it is, the use of a drain system in the invert would minimize this problem. The optimum design of the mixture proportions of the backpacking concrete, using a finely ground cement that would have a higher water requirement per unit weight of cement, would help to minimize bleeding.

The volume of water lost to bleeding plus some small volumetric changes in the air in the concrete might result in some plastic shrinkage of the concrete before hardening of the concrete begins. This shrinkage was in evidence for all three concretes used in this program and can be seen in Figure 4.4 for the cellular concrete and Figure 4.5 for the vermiculite concrete. A small void occurring at the crown of a rock opening may not pose any problems; however, voids adjacent to the structural liner are not desirable. To compensate for the plastic shrinkage, small quantities of finely divided aluminum powder can be added to the batches of concrete. The aluminum powder reacts with the alkalies in the cement and forms hydrogen gas, thus resulting in a slight expansion of the concrete. The expansion process is not instantaneous but does occur within the setting time of the cellular concrete. The amount of aluminum powder to be used should be determined on the basis of the actual ingredients to be used on the job. By varying the amounts of aluminum powder for a given concrete, the desired expansion can be obtained.

Figure 4.6 shows the effect of varying amounts of aluminum powder in the same concrete.

No special preparation was given to any cold joints in the large concrete sections of this study before fresh concrete was placed against them. Indications from a horizontal joint study of cellular concrete (Reference 3) are that the downward bleeding of the excess mixture water results in some deposition of finer cement particles in the joint area, thus enhancing the bond and strength of the joint. The cold joints in the prototype sections should be protected from construction traffic abuse and the infiltration of water from outside sources. If the cold joints are damaged, the surface can be easily raked up to any desired depth and the damaged portion removed. The cold joints should be free of debris and dust before the placing of the next lift of concrete.

4.2 RATE OF HARDENING

Rate-of-hardening tests were made on all three types of concrete to determine if any of the three would harden and develop strength faster than the others, thus permitting earlier form removal and earlier access by construction traffic. Earlier form removal and access may reduce the total time normally required to complete the job.

The cellular concrete samples (Figure 3.6) began stiffening

sufficiently to resist the penetration of the Proctor needle 9 to 11 hours after casting. The vermiculite concrete and the polystyrene concrete (Figure 3.6) began stiffening at 5 to 7 hours and 5 to 8 hours, respectively.

The increase in stiffening time for the cellular concrete was expected because the foaming agent used in developing the preformed foam contained some aliphatic fatty acids and their salts which will cause some slight retardation of the setting of the cement. Because of the higher molecular weight of these acids and salts when compared with that of the acids and salts of conventional water-reducing and set-controlling admixtures for concrete, large quantities of these acids and salts per unit volume of cement paste would be necessary to cause any appreciable retardation; and large quantities per unit volume of paste generally are not present in cellular concretes.

The amount of time elapsing between casting and form removal in the prototype will depend not only on the stiffening characteristics of a backpacking concrete as determined by the rate-of-hardening test but also on the amount of material placed, the elapsed time of placing, and the ambient and concrete temperatures associated with the placing. During large-volume placing operations that involve a considerable time period, the concrete in the lower portions of the lift will harden well before the concrete in the upper portions.

During the hardening of the concrete, heat is released due to hydration of the cement (see Section 4.5) and causes the temperature in the unhardened upper portions of the lift to be elevated somewhat, thus causing an acceleration of the hardening in the upper portion. This accelerated hardening may allow the forms to be removed earlier than indicated by a rate-of-hardening test.

The actual time of form removal and an acceptable time for access under prototype conditions should be a matter of engineering judgment, combining the knowledge of the stiffening characteristics of the material as determined from the rate-of-hardening tests with actual on-the-job observations of the material. For planning purposes, a conservative estimate of form-removal time for the expected conditions associated with the proposed field test would be 12 hours after completion of the placing of the concrete.

4.3 COMPRESSIVE STRENGTH

The ideal stress-deformation curve for an efficient backpacking material is represented by the relation shown in Figure 4.7 for an elastoplastic material (Reference 1). Under the application of pressure, the material behaves quasi-elastically until the yield point, or crushing point, is reached. The voids in the material then begin to collapse with only small increases in the pressure, and a reasonably linear second slope, usually called the crushing plateau,

develops. The crushing plateau may be flat or have some positive slope, depending on the composition of the backpacking material. The crushing continues until most of the voids have collapsed. The material then begins to lock up, with only small additional deformations occurring for additional increases in pressure.

Typical stress-deformation curves for the three concretes investigated are shown in Figures 3.2, 3.4, and 3.5, for conditions of both ideal curing and oven-dried curing. All three concretes exhibit the desired behavior under static loading conditions. The actual proportioning of the ingredients of the concretes in order to obtain a desired strength at a particular age can be determined using the actual job materials, once these requirements are known. Some difficulty may be encountered in developing polystyrene concretes with very low stress levels because of the extremely low water-cement ratios that may be required to provide the sufficiently sticky cement paste needed to prevent the lightweight polystyrene beads from floating out of the unhardened concrete. Low water-cement ratios generally produce stronger concretes than higher water-cement ratios.

It is a well-established fact that concrete will continue to gain strength with increasing age under ideal curing conditions. The low-density concretes investigated in this study are no exception, as shown in Figures 3.1 and 3.3. The curing conditions of the backpacking in prototype sections may approximate ideal conditions and

thus result in a continual strength gain throughout the useful life of the material. The amounts of strength gain at later ages of the concrete will be very small, however. To ensure a strength level of the concrete that is commensurate at any age with the design of the liner, it would be desirable to base the design strength of the concrete on its strength at some age greater than the usual age (28 days) used for evaluation of concrete strengths. If it is desirable, based on other considerations, to design the concrete for early age strength and the strength gain-age history of the concrete is known, the concrete can be designed for a reduced crushing strength at early ages so that the strength-gain-with-age characteristics of the concrete will bring the strength to the desired level at later ages.

4.4 IN SITU METHODS OF DETERMINING DENSITY VARIATION

In order to obtain a uniform compressive strength throughout the backpacking concrete placed around a tunnel liner, it is essential that the density of the concrete be uniform throughout. Changes in the high air contents associated with low-density concretes can occur during placing if proper care is not exercised. The change in air content causes changes in density and, hence, in cement content which is directly related to compressive strength. Density changes due to possible changes in the amount of aggregate

or in the apparent specific gravity of the aggregate due to crushing of the voids in the aggregate may also occur. Changes in these factors also change the cement content of the concrete. Although the greatest care may be exercised during batching and placing of the concrete, there is always the possibility that, once the material is in the form and/or the concrete inspector's control of the concrete is at a minimum, density variations may occur for some unexpected reason.

In the model section utilized in this program, it was possible to completely sample the concrete after it had hardened to determine any density variations (Section 2.6.3 and Tables 3.1 to 3.4). In the prototype, however, this extensive sampling may not be practical, and other methods of determining the uniformity of the material must be considered.

During this study two possible methods of in situ density variation determination were investigated. The first method utilized the effect of density variations on the maximum temperatures developed in the concrete. The second method utilized ultrasonic pulse velocity measurements of the concrete for which density and strength correlations could be made. Finally, as a check on these methods, the entire section was thoroughly sampled to obtain data on actual density variation throughout the section.

4.5 EFFECT OF DENSITY VARIATION ON HEAT DEVELOPMENT

When water is added to portland cement, hydration of the compounds forming the cement begins. The hydration of these compounds is exothermic, with certain amounts of heat, commonly called the heat of hydration, being liberated for certain volumes of cement. The heat of hydration is defined as the quantity of heat, in calories per gram of unhydrated cement, obtained upon complete hydration at a given temperature.

The rate of heat development as well as the total heat depends on the composition of the cement. The fineness of the cement, which determines the amount of surface area per gram of cement that is available for hydration, influences the rate of heat development but not the total heat liberated. The temperature at which the hydration takes place also greatly affects the rate of heat development.

For a unit volume of cement paste containing sufficient moisture to effect and maintain hydration, the heat rise can be accurately measured while the paste is curing under adiabatic conditions or it can be approximately determined from the following equations (Reference 10):

$$T = 1.8\ C\ H/S \tag{4.1}$$

Where: T = temperature rise, $^{\circ}F$

C = cement content, grams of cement per grams of concrete

H = heat of hydration of the cement, cal/g

S = specific heat of the concrete, BTU/lb/F

The temperature rise when calculated with Equation 4.1 is usually lower than that which is actually observed in an adiabatic test. The heat of hydration of the cement at any time prior to completion of the hydration can be approximated as:

$$H = H_o \left(1 - e^{-rt}\right) \tag{4.2}$$

Where: H = heat of hydration at time, t , cal/g

H_o = ultimate heat of hydration of the cement, cal/g

e = the base of natural logarithms

r = a constant depending on the type of cement used

t = time elapsed subsequent to the mixing of the cement and water, hours

When other ingredients, such as air and/or aggregate, replace a portion of the paste or the water content changes, the total heat developed would, in most cases, change as the cement content C and the specific heat of the concrete S change. Temperature rise is reduced almost linearly with reduction in cement content and, conversely, is increased with increases in cement content. Heat-development records obtained from thermocouples embedded throughout a concrete mass should indicate variations in cement content that can be related to density variations for the concrete in question.

4.5.1 Cellular Concrete. A summary of the average maximum temperature, unit weight, and oven-dry density for each lift of the cellular concrete is shown in Table 3.7.

Assuming that the water-cement ratio of the cellular concrete remained constant for each lift, the cement content expressed in grams of cement per gram of concrete also remained constant. Differences in density between lifts would then result primarily from changes in air content. In utilizing Equation 4.1 to compare two lifts of concrete based on these assumptions, a comparison expression can be written in the form:

$$T_1 s_1 = T_2 s_2 \qquad (4.3)$$

Where: T_1 and T_2 = temperature developed in two lifts

s_1 and s_2 = specific heat of the concrete in the two lifts being compared

The specific heat of the concrete will vary only slightly, however, with small changes in air content and, as can be seen from Equation 4.3, will not appreciably affect the temperature difference between lifts.

If it is assumed that both the air content and the cement content changed proportionately from the theoretical mixture design to result in a design density approximating the theoretical design

density, then both the cement content and the specific heat of the concrete, as shown in Equation 4.3, would be changed. The largest maximum temperature differential observed was 11 F and occurred between lifts 2 and 3. If it is assumed that the estimated 160+ F for lifts 2R and 2L is on the high side and that 149 F for lift 3 is low with respect to an approximate mean of 155 F for the entire section, it would be necessary to have a variation from the theoretical water-cement ratio of ± 0.2 to effect the temperature change of ± 6 F. This amount of variation in the water-cement ratio is highly improbable because of the controls exercised during placing. Small differences in the water-cement ratio, and hence the cement content of the cellular concrete, should not greatly influence the temperature difference between lifts.

It must be kept in mind that the heat-development data were obtained from concrete whose formwork allowed a transfer of heat from the system to the air. This factor can account for some variations in the total heat measured in the system. Temperature variations due to this condition may be reduced in the prototype sections if the confining rock behaves as a semi-infinite heat sink.

In summary, it appears that the variations in maximum temperatures witnessed between lifts were not predominantly a product of the proportioning of the materials but were considerably influenced by the configuration of the test, and that the heat developed

throughout the section was fairly uniform, thus indicating no appreciable density variations throughout. This was substantiated by the hardened density sampling results (Table 3.2).

4.5.2 Vermiculite Concrete. A summary of the average maximum temperature, unit weight, and oven-dry density for each lift of vermiculite concrete is shown in Table 3.7.

A comparison of the average maximum temperatures of lifts 2L and 2R with those of lifts 1 and 3 shows that a temperature differential of 10 F and 8 F, respectively, exists. While there appears to be no appreciable difference in the average plastic density for each lift, there is a difference in oven-dry density as great as 3.5 pcf between lifts 2R and 3. The increased density was probably due in large part to a loss in air content during pumping and placing. The loss in air content should result in an increase in cement content with possible changes in the specific heat of the concrete which could account for the temperature differential. As mentioned in the discussion of the cellular concrete heat-development data, the variation could also be due, in part, to the test configuration. It is difficult to determine the amount of influence which either the proportioning of the materials or the test configuration had on the temperature differential.

In summary, it appears that within limitations of the test and its equipment, the maximum temperatures developed throughout the

section were fairly uniform and where higher average maximum temperatures were noted, increased densities were also noted.

4.5.3 Polystyrene Concrete. The heat-development curves shown in Figure 3.9 and the summary data in Table 3.8 show that as the depth of the concrete increased from the lift 1 surface, the maximum temperature increased, thus indicating an increasing paste concentration with increasing depth. The very light polystyrene beads had a tendency to float on the heavier paste, resulting in an aggregate concentration near the top of the lift and a paste concentration near the bottom.

Some temperature differences can be noted from the front to the rear of the section for the thermocouples placed nearest the surface of the lift. The pushing action of the concrete, caused by the pumped flow of concrete from front to rear of the section, caused some additional segregation as the lighter, bulkier aggregate was pushed ahead, leaving the heavier paste behind.

The oven-dry densities of the hardened concrete samples did not reflect gross density variations because the samples were taken from the approximate center of each of the wedges cut from the entire mass. The extreme differences in paste concentration were at the top and bottom of the lift where no samples were obtained. The oven-dry density samples reflected an average density for each wedge.

Although locations of the oven-dry density samples resulted in

their ineffectiveness for the purposes of indicating the segregation of the lift, the segregation of the aggregate and paste could be noted visually. Figures 4.2a and 4.2b show the front and rear ends, respectively, of the formwork with the bulkhead removed. The paste is concentrated on the bottom of the section in both cases. Inspection of the entire hardened mass during the hardened density sampling operation revealed that this condition prevailed over the entire length of the bottom of the section. The beads visible in Figure 4.3 are at the top of lift 1 and are bound together by very little hardened paste. Modification of the mixture design for the second lift in an effort to prevent this segregation was of only minor benefit.

In summary, it was determined that heat-development records obtained from the thermocouples embedded in the first lift of the polystyrene concrete mass were effective in indicating that aggregate-paste segregation and, hence, density variations had occurred in the lift. This segregation was substantiated visually.

4.6 EFFECT OF DENSITY VARIATION ON ULTRASONIC PULSE VELOCITY

The use of ultrasonic test equipment for evaluating the uniformity of concrete in situ is well established. The background, theory, concrete property correlations, and evaluation of the characteristics of concrete from sonic tests are adequately

summarized in Reference 11 and will be only briefly reviewed in this report.

The methods used in an ultrasonic evaluation of concrete determine the time of travel of a pulse or train of compressional waves through a known path length through the concrete. A generated voltage pulse is sent to a transmitter transducer placed on one surface of the concrete where the electrical pulse is transformed into a mechanical (ultrasonic) pulse. This ultrasonic pulse propagates through the concrete and is picked up by a receiver transducer on the opposite surface of the concrete. The travel time of the pulse through the concrete is recorded and the pulse velocity, in feet per second, is calculated.

For the purposes of determining the uniformity of the backpacking concrete, correlations between the ultrasonic pulse velocity and age, and/or density can be developed. Figures 4.8 and 4.9 represent some actual correlations obtained from 6-inch-diameter by 12-inch-long cellular concrete cylinders with a mixture proportion almost identical with that used in this study. In developing these correlations, however, factors such as: (1) the fine and coarse aggregate, if any, (2) relative mixing water content, (3) cement content, (4) air content, (5) absorbed moisture in the hardened concrete, (6) effect of specimen size, (7) path length in the concrete, and (8) condition of the concrete at the time of test,

should be considered and controlled (Reference 12). Once these correlations have been determined, it should be easy to discern when the concrete is not uniform since the ultrasonic pulse velocities measured through the prototype will vary appreciably from the normal at points where the concrete is not uniform. The exact reason for the nonuniformity may not be determinable directly from the velocity measurements, but must be left to the judgment of the person interpreting the results of the measurements.

4.6.1 Cellular Concrete. The ultrasonic pulse velocities shown in Table 3.6 for the hardened cellular concrete mass were all determined on the same day. Shortly after the readings were made, the concrete was cut into smaller wedge sections for the oven-dry density evaluation. Because the concrete in the various lifts had been placed on different days, the velocities measured in lift 1, lifts 2L and 2R, and lift 3 were obtained at concrete ages of 14, 10, and 6 days, respectively. The typical sonic velocity-age relation in Figure 4.8 shows that velocities increase rapidly in the time interval between 6 and 14 days. This increase for the velocities shown is also evident in Table 3.6.

The curve shown in Figure 4.8 is representative of the cellular concrete used in the cellular concrete placing operation; however, the values obtained in the large section were considerably higher than those obtained for smaller cylinders. This is contrary to what

has normally been observed in the past. The increase is probably due to an indirect path length that carried the pulse signal to the metal formwork enclosing the concrete (Figure 4.10). The sonic velocity of the metal is much greater than that of the concrete and thus would cause the pulse to travel faster than it would through the concrete and to arrive at the receiver before the signal through the concrete arrives, despite its increased path length. The solid line in Figure 4.10 represents the desired path length through the concrete, while the broken lines represent the probable path the pulse followed. A portion of that probable path was in the concrete, while a portion was in the metal liner. This would account for the increase in velocity with age because the concrete path was experiencing a velocity increase even though there was no velocity change in the metal.

Evidently, the 2-foot thickness of the concrete was not great enough to allow the signal following the shortest path length through the concrete to arrive before the signal following the longer but faster path length through the concrete, then metal, and, finally, concrete again. This same problem may exist in the prototype if the signal passes into the adjoining rock or liner, both of which may have sonic velocities greater than the backpacking concrete. In these cases, the thickness of the backpacking must be such that the total composite velocity along the indirect path length is less than

the true velocity along the shortest path length. An expression for this can be written as:

$$\frac{L'_c}{t'_c} + \frac{L_m}{t_m} + \frac{L''_c}{t''_c} \leq \frac{L_c}{t_c} \qquad (4.4)$$

Where: L'_c and L''_c = indirect path length through the concrete

L_m = path length in the confining media or liner

L_c = shortest path length through the concrete

t'_c and t''_c = effective time of travel through concrete of path lengths L'_c and L''_c, respectively

t_m = effective time of travel through confining media or liner of path length L_m

t_c = effective time of travel through concrete of shortest path length

The terms in Equation 4.4, with the exception of L_c and t_c, can be approximately determined in the laboratory for various types and thicknesses of backpacking.

Other problems associated with the use of ultrasonic test equipment on a prototype section for purposes similar to those of this study can be foreseen. When evaluating competent structural concrete having sonic velocities in excess of 10,000 ft/sec, the maximum path length that can be obtained from the presently available commercial equipment is 50 feet. The very low velocities and increased damping

of the signal associated with the low-density backpacking concrete should reduce this path length considerably. For very long prototype sections, the use of ultrasonic test methods may not be feasible. Depending on construction techniques, the placing of the transmitter transducer and receiver may also render this test method impracticable.

Because of the factors mentioned in the previous paragraphs, it is believed that the sonic velocities obtained from the cellular concrete mass were not representative of the concrete. Because of the assumed indirect path length followed by the pulse, the velocities could not have indicated whether any large areas of nonuniformity existed. The test results did indicate the existence of an age-velocity increase trend, however, and also called attention to the limitations of using the sonic method for evaluating the uniformity of the backpacking concrete for jobsite conditions.

4.6.2 Vermiculite Concrete. The data shown in Table 3.6 do not reflect the same age-velocity increase trend that the cellular concrete section did. All the velocities, regardless of the age of the concrete, appear to be in the same general range. It is not known whether this is representative of this type of concrete, as age and/or density versus sonic velocity correlations were not established for the vermiculite concrete prior to the obtaining of

ultrasonic pulse velocity data from the hardened section.

The same problems associated with the cellular concrete section evaluation probably existed for the vermiculite concrete section, and it is believed that the data in Table 3.6 are not representative of the vermiculite concrete.

4.7 SAMPLING OF HARDENED CONCRETE TO DETERMINE DENSITY VARIATION

To determine the uniformity of the hardened concrete in prototype sections, actual samples of the concrete can be drilled or cut from the sections and their densities determined. Experience in drilling cellular concrete cores in the laboratory indicated that the drilling approach may not be practical due to the very brittle nature and low strength of the concrete, which usually results in a fractured and broken sample after drilling. It is possible that a sampling tube that is simply forced into the concrete can be used because it would apply little or no vibration or twisting loads to the material. This technique was used successfully to obtain relatively short samples, but its practicality for obtaining longer samples is not known. Samples can always be cut from the prototype sections, but this limits the extent to which the concrete can be sampled because of the limited surfaces and opportunities during placing to do this type of sampling. At present no suitable method of sampling the prototype sections is known.

4.7.1 Cellular Concrete. The data presented in Tables 3.1 and 3.2 for the preliminary and cellular concrete placing operations, respectively, indicate that the cellular concrete for both operations was fairly uniform from the top to the bottom and from the front to the rear of the section. The material did have a tendency to be slightly denser at the cold joints, however. No major problems with respect to density variations were noted for either section.

4.7.2 Vermiculite Concrete. The densities from the top to the bottom of the vermiculite concrete section as shown in Table 3.3 indicated that the concrete was fairly uniform with the exception of some heavier portions in wedges 2, 3, and 7. An inspection of the densities for the slice sections revealed that the heavy portions occurred in slices A and B.

It is of interest to note that the heavier portions of wedges 2, 3, and 7 occurring in slices A and B were immediately adjacent to the openings in the bulkhead through which the concrete was pumped into the form. After entering the formwork, the concrete was required to flow the length of the form and also to rise an additional 12 to 18 inches above the discharge opening in the form. Based on the increased densities around the openings, it is suspected that the increased resistance to flow due to the fresh material already in the form caused some consolidation of the aggregate and paste plus some loss of air content in the area adjacent to the discharge openings.

This consolidation and probable lumping of the aggregate and paste would explain the segregated appearance of the vermiculite concrete surface in Figure 4.1. If it is assumed that the submergence of the discharge end of the placing hose resulted in the localized increased densities, it can then be speculated that if the discharge hose had been kept at or above the surface of the concrete during placing, the hardened densities throughout the entire vermiculite concrete section would have been fairly uniform.

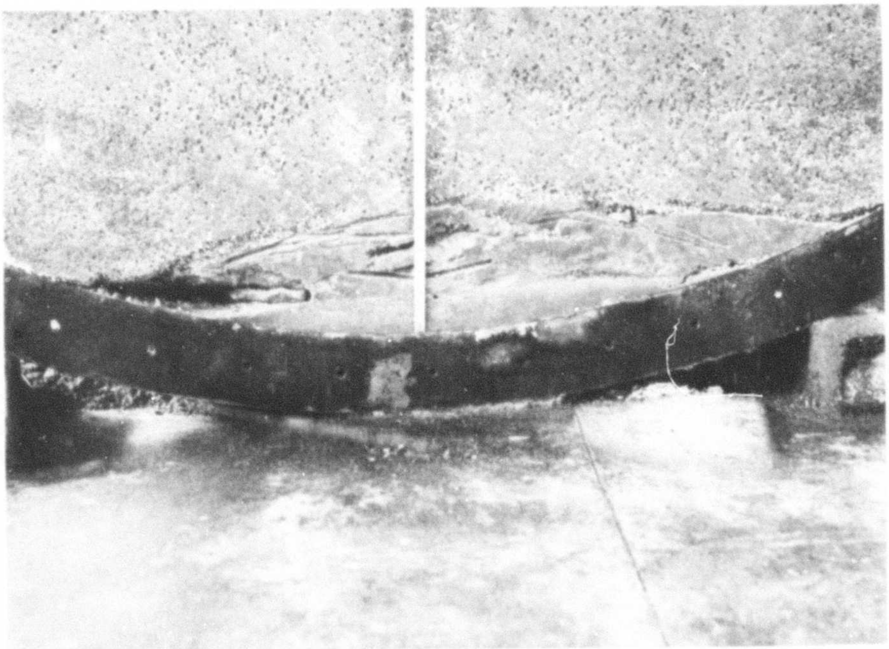
Although increased densities adjacent to the bulkhead openings were not noted during the sampling of the cellular concrete section, it should not be assumed that this cannot happen in other cellular concrete sections. The fact that the cellular concrete does not contain a collapsible aggregate (air voids can compress some, however) is favorable for reducing the probability of this occurring. The submergence of the discharge end of the placing hose is not desirable for any of the types of concrete evaluated for use as backpacking and should be avoided if at all possible. The prototype sections will be much larger than the model section of this study and, due to probable methods of construction, will present such configurations that the maintaining of the discharge end of the hose at or slightly above the surface of the concrete being placed should be no great problem.

4.7.3 Polystyrene Concrete. The oven-dry densities of the polystyrene concrete as shown in Table 3.4 do not reflect the gross

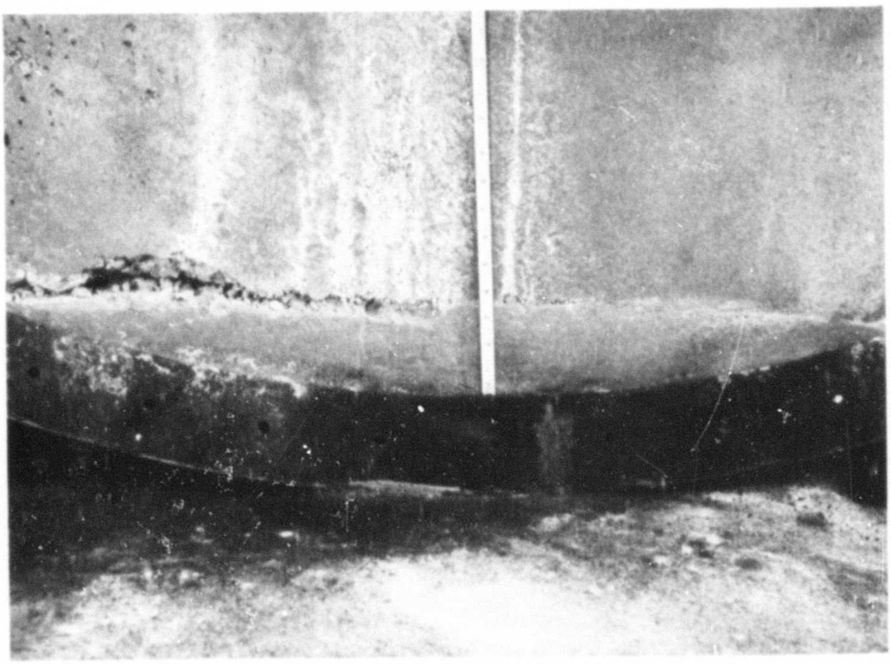
density variations that obviously occurred (Figures 4.2 and 4.3) throughout the section because all of the samples were taken from the approximate centers of the wedges cut from the large mass and reflect only an average density for each wedge. The extreme differences in density occurred at the top and bottom of the lifts.

The fact that the hardened density samples as taken did not indicate the actual variations in the entire mass calls attention to the necessity for any hardened density sampling of the prototype sections to be very thorough and extensive in order to provide a reliable indication of the uniformity of the section. Since this problem is caused by the aggregate separating from the paste, it is probably unique to the low-density aggregate concretes and could be greatly minimized or eliminated by the optimization of the mixture proportions with respect to handling and pumping characteristics of the concrete.

Figure 4.1 End view of vermiculite concrete section showing segregated appearance of the concrete.



a. Front end.



b. Rear end.

Figure 4.2 Views of the polystyrene concrete section showing the paste concentration of lift 1.

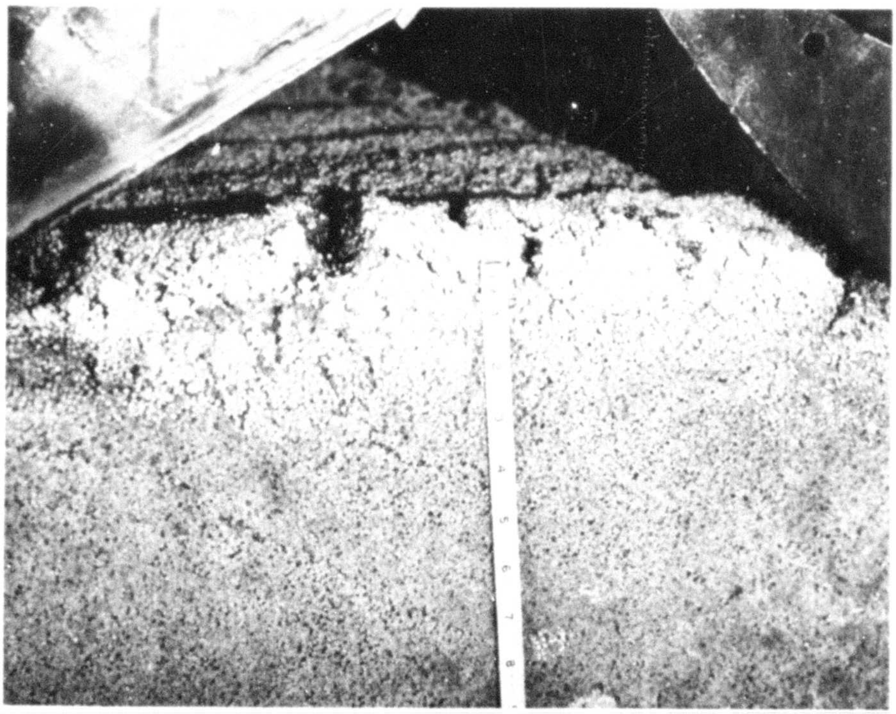
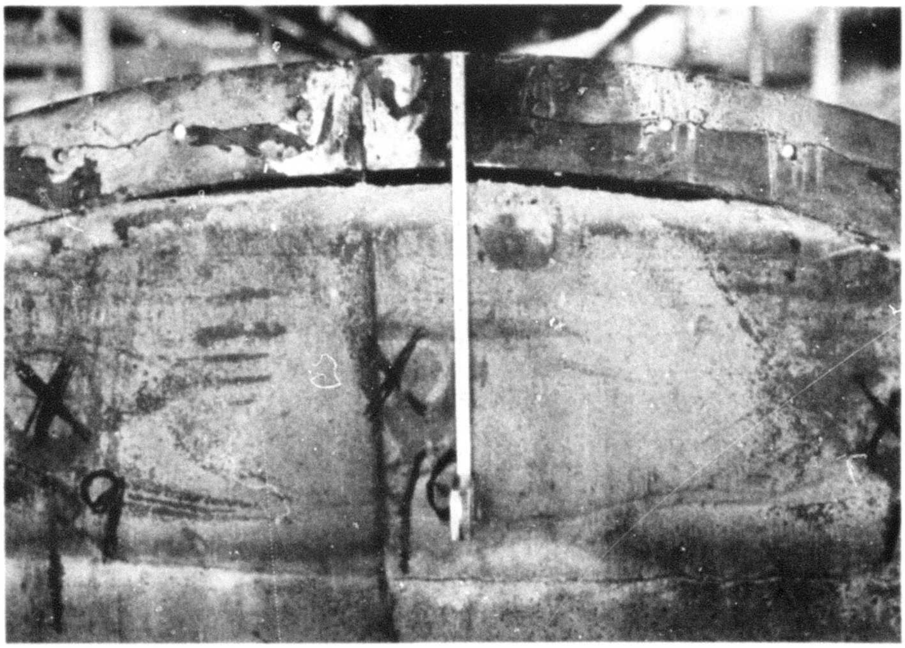
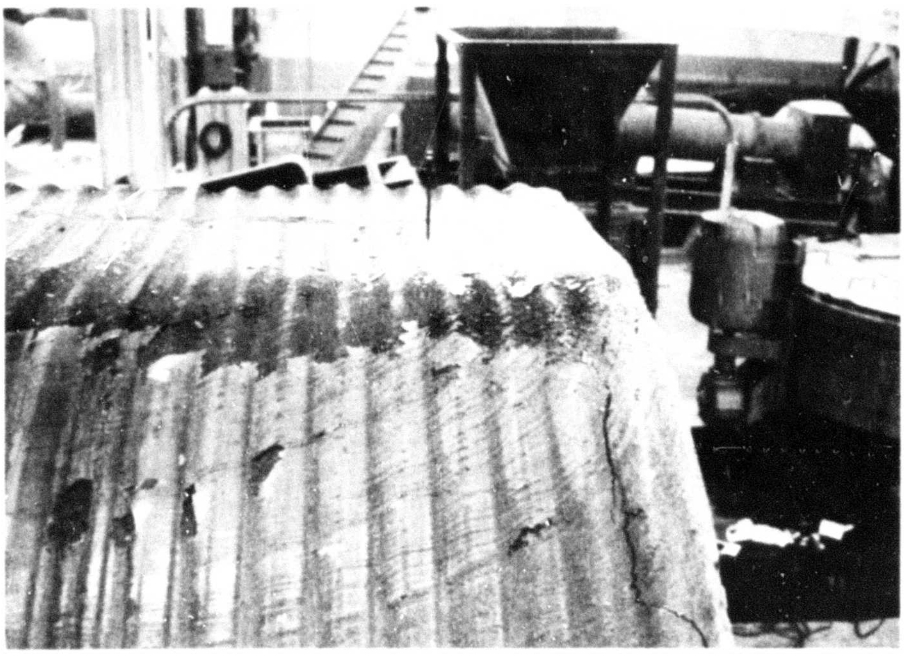


Figure 4.3 Front end view of the polystyrene concrete section showing the bead flotation of lift 1.

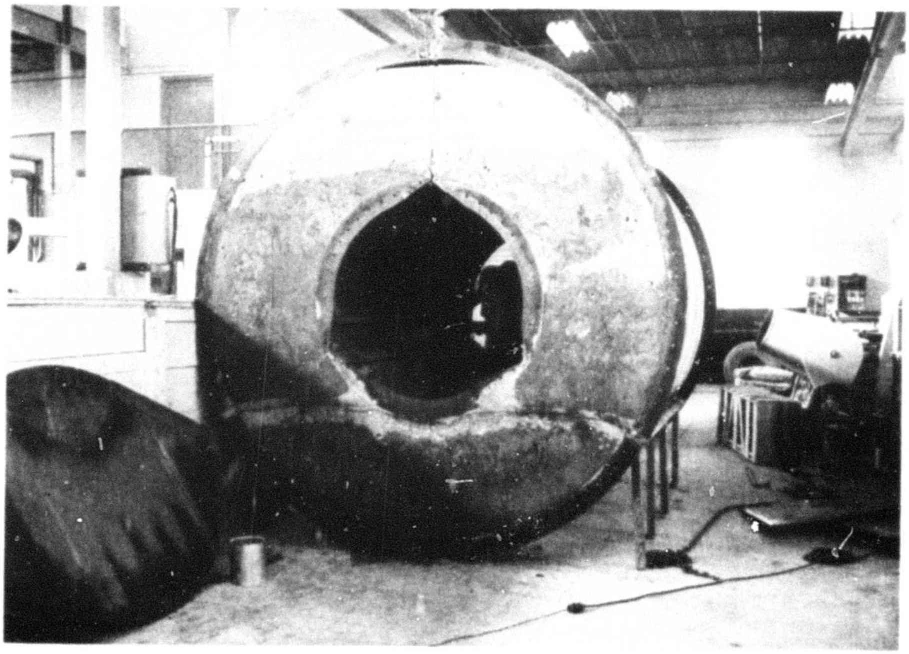


a. End view.

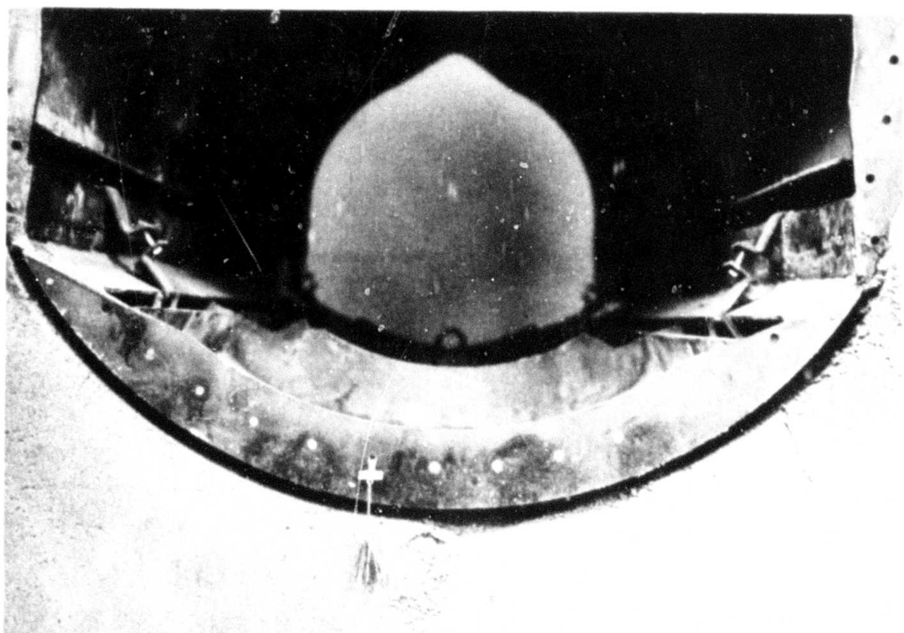


b. Side view.

Figure 4.4 Views of cellular concrete section showing shrinkage at the crown.



a. At the crown.



b. At the invert of the liner.

Figure 4.5 End views of vermiculite concrete section showing shrinkage.

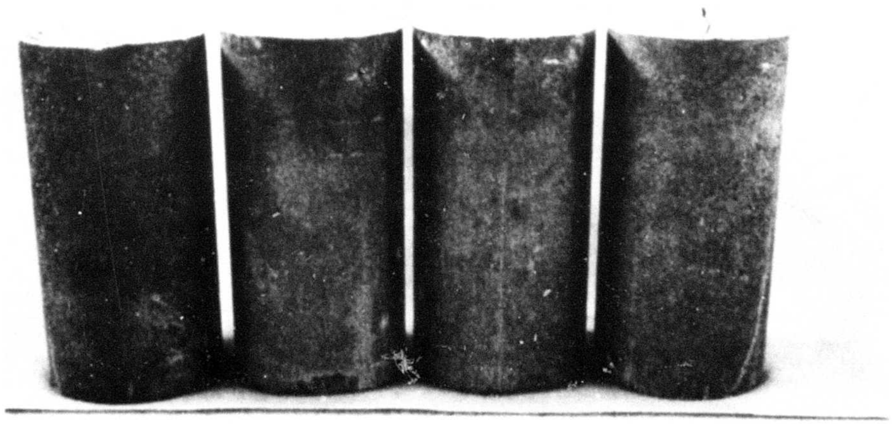


Figure 4.6 Effect of varying amounts of aluminum powder on cellular concrete.

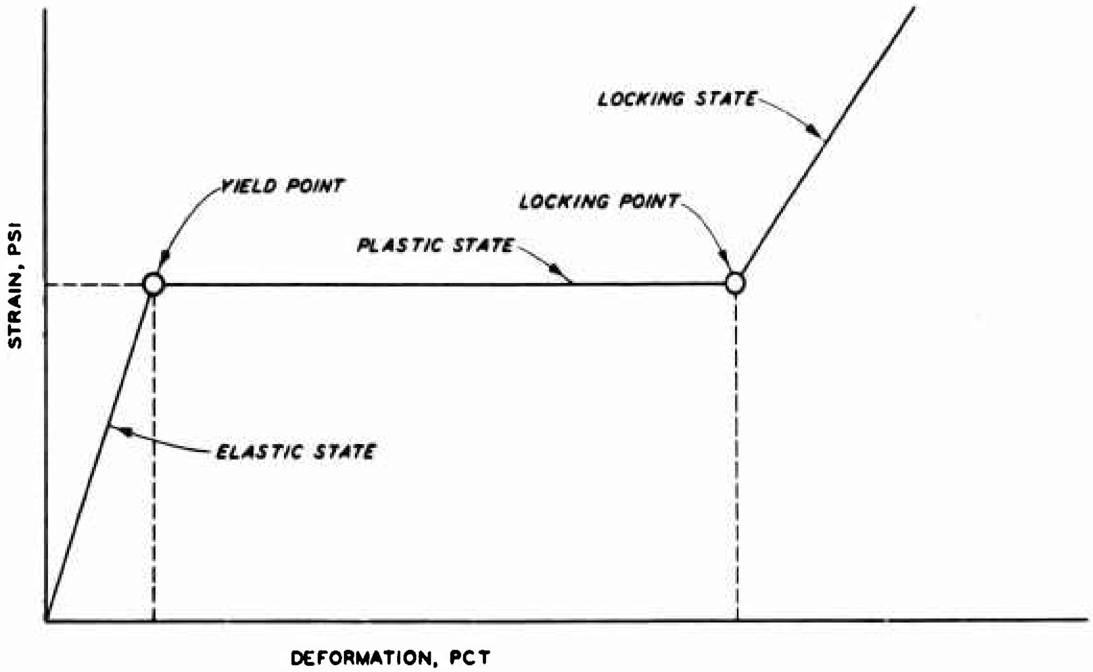


Figure 4.7 Ideal stress-deformation relation for an elastoplastic (linear-plastic-linear) material.

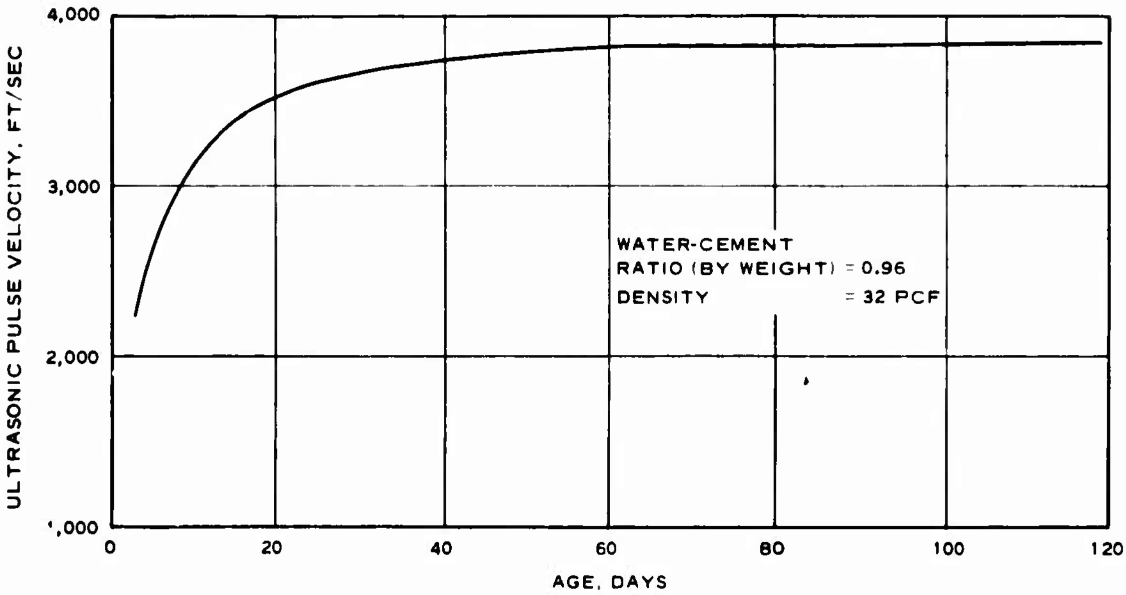


Figure 4.8 Typical ultrasonic pulse velocity versus age of concrete relation for a cellular concrete.

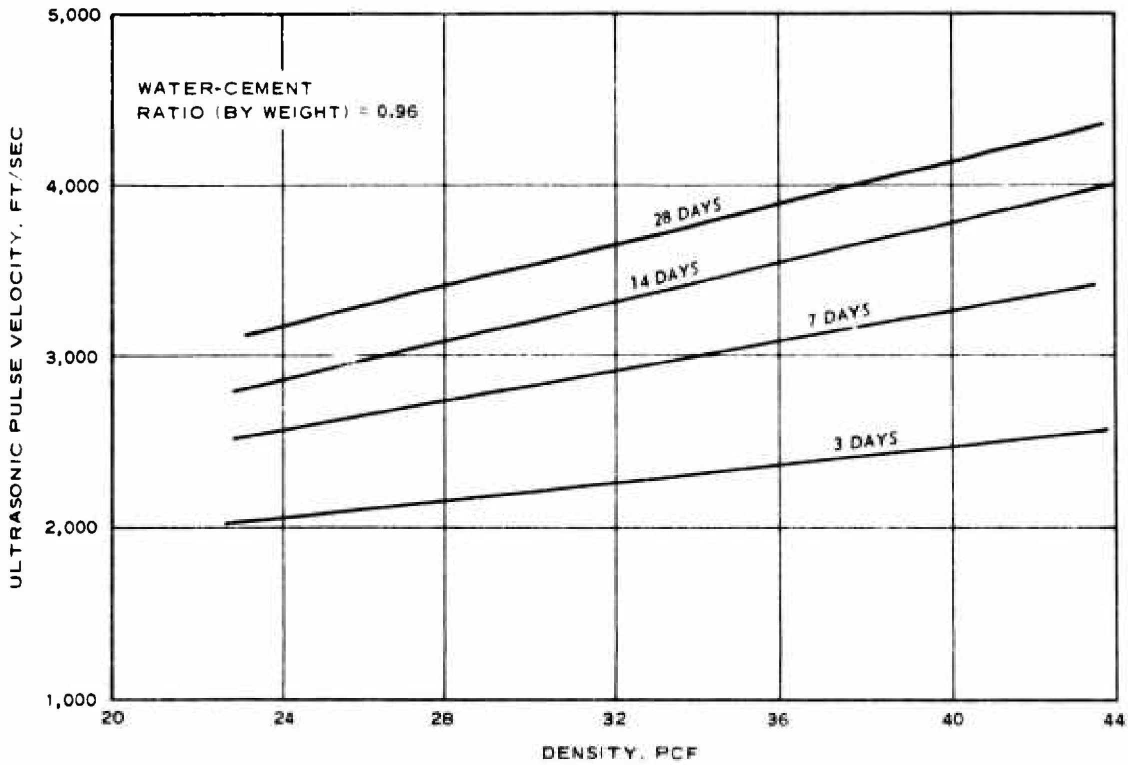


Figure 4.9 Typical ultrasonic pulse velocity versus density relation for a cellular concrete.

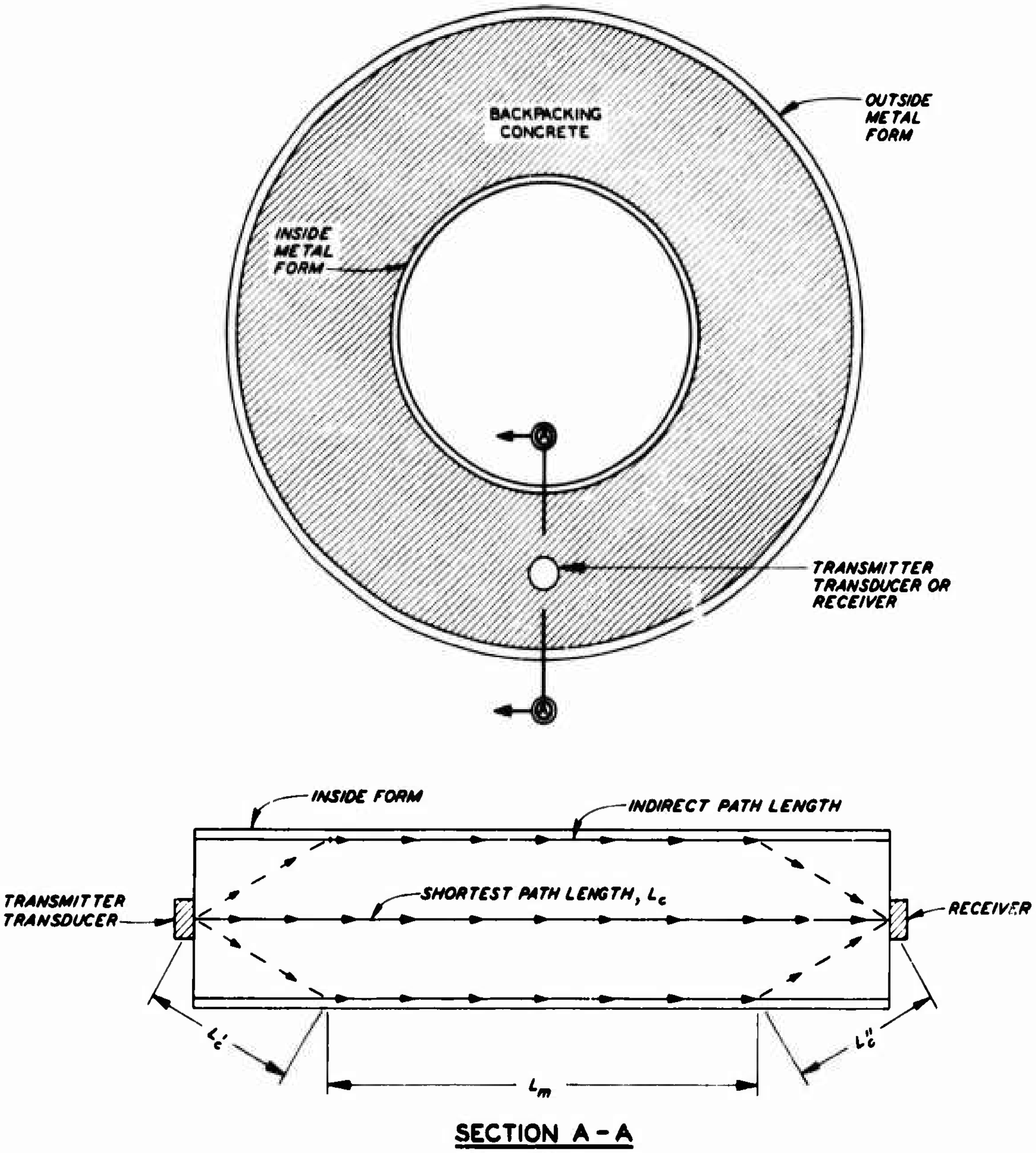


Figure 4.10 Typical ultrasonic pulse velocity path lengths.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The objective of this study was to investigate three insulating concretes being considered for use as backpacking material to determine their handling, mixing, and placing characteristics as well as the density, variation, plastic shrinkage, aggregate segregation, and rate of hardening occurring in large sections made with each concrete, and to determine the problems that may be associated with the use of these concretes in a prototype situation.

5.1 CONCLUSIONS

As a result of observations made during the Shock-Absorbing Materials program (References 1 to 7) and of studies of the test results of this investigation, the following conclusions can be drawn:

5.1.1 Storage and Handling. Less storage space and material handling requirements are associated with the use of cellular concrete when compared with low-density aggregate concretes. This factor should be considered when the construction site and working areas are remote, and where bulk aggregate and/or concrete-haul distances are not economically attractive. If low-density aggregate concretes are used, the aggregate can be expanded at the construction site, thus reducing the volume of material that must be hauled to the site.

5.1.2 Batching and Placing Equipment. Horizontal-drum paddle mixers appear to be best suited for the batching of backpacking concretes. Other types of mixers can be used but should be thoroughly investigated before they are put into operation. Open-throat positive-displacement pumps appear to do an excellent job of pumping the high-air-content backpacking concretes and should be used when possible. Mixers and pumps should be operated at constant speeds compatible with the required density control. The constant speed of operation will aid in batch-to-batch reproducibility.

5.1.3 Batching and Placing Techniques. The hand-timing method of introducing preformed foam into a cement slurry or a cement slurry-low density aggregate combination in order to provide the desired air content may not be practical on prototype jobs. The use of a reset electric timer and solenoid valves for repetitive foam cycle discharge would be more desirable. The use of an NVR for air entrainment of the large amounts of air required in the low-density aggregate concretes may not be practical in a prototype situation; however, the preformed foam can be used in this capacity and may result in improved batch-to-batch reproducibility.

Unit weight at the discharge end of the placing hose can be used as a quality control measure. The unit weight can be correlated with strength through laboratory development work. Density variations occurring during pumping should be determined on the job for

the materials, mixing, and pumping speeds, type and length of placing hose, and the maximum differential heads actually used on the job and then compensated for accordingly.

During pumping, the discharge end of the placing hose should not be submerged in the concrete if at all possible, but should be kept at or near the surface of the freshly placed concrete so that the possibility of localized density variations is minimized.

Some excess mixture water can be expected for all of the backpacking concretes. If the amounts of excess water are such that bleeding into the invert of the section is anticipated, a drain system in the invert can be used. The use of a finely ground cement, such as Type III portland cement, may help to minimize the amount of bleeding that might occur.

Some plastic shrinkage can be expected for all of the backpacking concretes. Small amounts of aluminum powder can be used to cause a slight expansion of the concrete during setting, thus compensating for the plastic shrinkage that may occur.

5.1.4 Mixture Proportions. Based on laboratory development work, the mixture proportions of each backpacking concrete generally can be optimized to result in a concrete that has the desired physical properties for a backpacking, and also the desired placing qualities.

5.1.5 Hardened Concrete Sections. The form-removal time should

be a matter of engineering judgment based on a combination of the stiffening characteristics of the concrete as determined by laboratory tests and actual on-the-job observations of the concrete.

No special preparation need be given to the cold joints; however, the joints should be protected from construction traffic abuse and the infiltration of water from outside sources.

The use of either the ultrasonic-pulse-velocity technique or the heat-development technique for determining in situ density variations does not appear to be practical. The use of hardened concrete samples, sawed or drilled from the concrete sections and then oven-dried, appears to be the best method of determining the density variations throughout the section. However, a good method or technique for obtaining these samples from prototype sections cannot be recommended at present.

Greater density variations were apparent throughout the hardened concrete sections when low-density aggregate concretes were used, because of localized aggregate segregation. This may be because the mixture proportions used in this study were not selected for optimum pumpability characteristics. The proper design of the concrete for these characteristics may eliminate the segregation problem.

5.2 RECOMMENDATIONS FOR FUTURE WORK

Before any of the three concretes investigated in this study

are used for backpacking in a prototype situation, additional studies of the following subjects would be desirable: (1) the optimization of the mixture proportions of the concrete to obtain the desired physical characteristics and pumping qualities; (2) development of larger, more sophisticated handling, batching, and placing equipment, systems, and techniques; (3) development of suitable hardened density sampling equipment and techniques; (4) heat-development characteristics of the concrete and methods of reducing the maximum hydration temperatures that will develop in the concrete.

APPENDIX A

FIELD PLACEMENT TRIAL OF A CELLULAR CONCRETE SECTION

A.1 BACKGROUND

A conference on backpacking materials for Project Pile Driver was held at the University of Illinois, Urbana, Ill., on 10 March 1964. The conference was attended by representatives of the U. S. Army Engineer Waterways Experiment Station (WES); U. S. Army Engineer Division, Missouri River (MRD); U. S. Army Engineer District, Omaha (OD); Air Force Weapons Laboratory (AFWL); Holmes and Narver, Inc. (H&N); Test Command, Defense Atomic Support Agency (TC-DASA); Reynolds Electrical and Engineering Company, Inc. (REECo); and University of Illinois (U of Ill.). The general purpose of the conference was to discuss the observations and test results presented in the main text of this report. Based on these results and other observations and comments made by WES personnel throughout the conference, it was unanimously decided to use cellular concrete as the predominant backpacking material for Project Pile Driver. It was also decided to build a test arch of cellular concrete to determine: (1) the ease of forming and placing, (2) if the arch would have strength enough to stand unsupported, and (3) the amount of settlement at the crown of the unsupported arch. The arch was to be made of cellular concrete having a compressive yield strength

of 150 psi and was to be circular in shape with an outside diameter of 16 feet. This appendix contains the observations and results of the placing of that arch of concrete.

A.2 FORMWORK

The placing operation was conducted in a tunnel at the U. S. Atomic Energy Commission's Nevada Test Site on 25-26 March 1964. The formwork had been prepared by REECo. The complete form was made of plywood, including the surfaces which normally would be rock in a prototype section. The end bulkheads were held together by snap ties. The complete formwork can be seen in Figure A.1. The formwork was 5 feet deep with an outside radius of 8 feet and an inside radius of 3.5 feet. Because of the small pressures anticipated, the formwork as constructed could be considered greatly overdesigned.

All visible joints and cracks in the form were sealed with plaster. The inside surfaces of the form had been coated with 30-weight motor oil to prevent the concrete from sticking to the form. Chicken wire was placed inside the form for the entire circumference of the section at a distance of approximately 6 inches from the inside form surface.

A.3 BATCHING AND PLACING EQUIPMENT AND PROCEDURES

The batching equipment used, though not ideally suited for the

operation, was the only equipment available on short notice. The foam-generating equipment (Figure A.2a) was the same as that used in the laboratory studies of cellular concretes at WES; its use is explained in Section 2.1.4. The mixing equipment (Figure A.2b) was the same type as used in the preliminary placing operation (Section 2.3). The pumping equipment (Figure A.3) consisted of an open-throat positive-displacement pump similar to that used for all four placing operations of the laboratory study (Section 2.3).

Batching procedures were identical with those described in Section 2.5.1. The concrete was pumped through a 2-inch-diameter rubber hose (Figure A.1) 50 feet long against a head differential of approximately 9 feet through an opening in the top of the formwork (Figure A.4a). Figure A.4b shows the chicken wire in the form and the surface of the freshly placed concrete.

A.4 MATERIALS

Bagged Type III cement was used in making the cement slurry. The same foaming agent as used in the laboratory study (Section 2.1.4) was used for this operation. The actual mixture proportions used for a single batch were as follows:

		Weight		Volume
		pounds		ft^3
Cement:	1.0 bag	94.0		0.478
Water:	10.0 gallons	83.3		1.335
Preformed foam:	54.3 sec (avg) =	17.2	(water) =	4.117
Total		194.5		5.930

Seventy-three batches of concrete were made having an average unit weight of 32.8 $\pm$ 0.5 pcf (for standard deviation of the mean) at the 95 percent confidence interval based on 36 unit weight checks.

A.5 PLACING OPERATION

The formwork contained approximately 15 yd^3 of annular space. Approximately 9-1/3 yd^3 of concrete was placed the first day. No batching or placing problems were encountered. The right side of the form was filled first to the top of the inner formwork; then the left side was filled and additional concrete placed over both sides to a depth of approximately 1 foot above the inner form surface. Because of the location of the cold joint that would result when the second lift was placed it could easily be determined if the closeness of the joint to the form would be detrimental to the integrity of the concrete section when the forms were removed. Some leaks occurred in the form along the bottom edges and at the snap ties but were easily sealed by dry-packing the plaster around the leaks.

The placing of the second lift was conducted the following day and filled the remainder of the formwork. Again, no problems in batching or placing were encountered. The opening through which the concrete was placed was filled to the top and finished to a fairly uniform surface in order to observe if any shrinkage occurred upon hardening. No leaks were observed the second day.

A.6 FORM REMOVAL

Prior to removal of the formwork from the hardened concrete section, REECo surveyors established a bench mark in the general area of the formwork and referenced the top of the crown of the inner surface of the formwork to the bench mark. Form removal was accomplished on 30 March 1964. Two views of the hardened concrete section are shown in Figure A.5. Based on the surveyors' reference points, no deflections of the concrete arch were noted one week after the forms were removed. Some shrinkage during hardening was noted at the top of the section.

A.7 CONCLUDING REMARKS

In general, the objectives of the field placing trial were satisfied and the three primary questions answered. First, no difficulty was encountered in placing the concrete; however, the equipment and procedures used resulted in a placing rate much too slow for larger prototype operations. Larger and more sophisticated batching and placing equipment plus improved techniques for both operations would be desirable. The formwork was satisfactory but was extremely overdesigned. In a prototype, the forming in most cases will probably have only end bulkheads that will be fitted to rock surfaces. It was noted that the cellular concrete leaked out of very small holes and cracks at almost negligible pressures,

thus indicating that the prototype bulkheads must be sealed so as to be watertight.

Secondly, the arch did have the strength to stand unsupported when the concrete was designed for 150 psi. No detrimental effects on the arch were noted due to the presence of a cold joint within 12 inches of the interior surface of the arch.

Finally, no measurable amounts of arch deflection were noted one week after the forms were removed. The shrinkage that occurred at the crown was not due to deflections but occurred during hardening. A definite need was indicated for use of aluminum powder in the final batches of concrete to cause an expansion if a tight seal at the crown is desired.

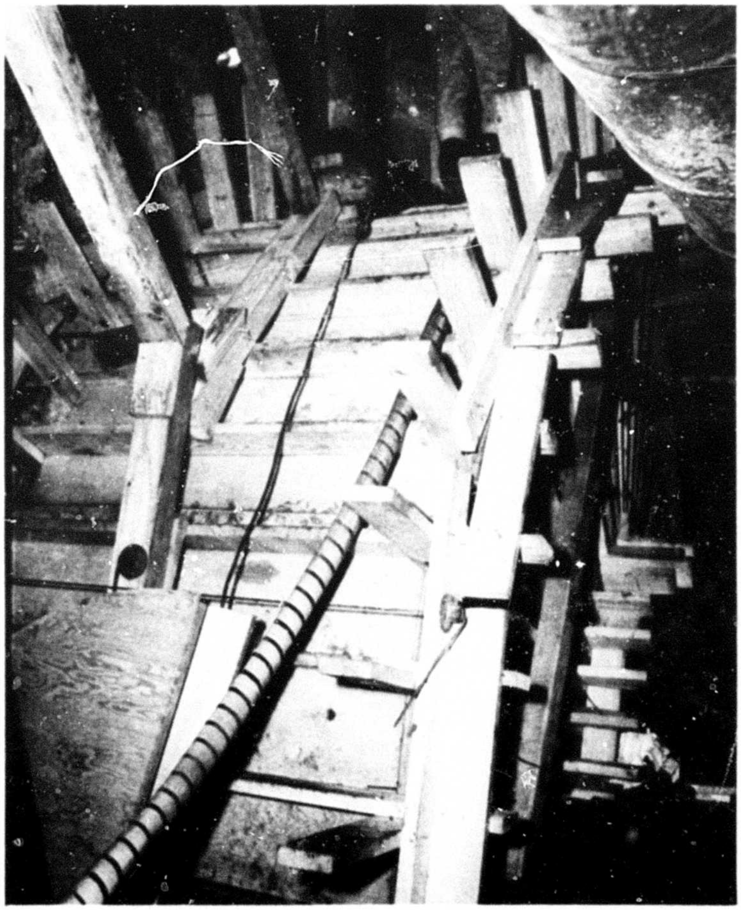
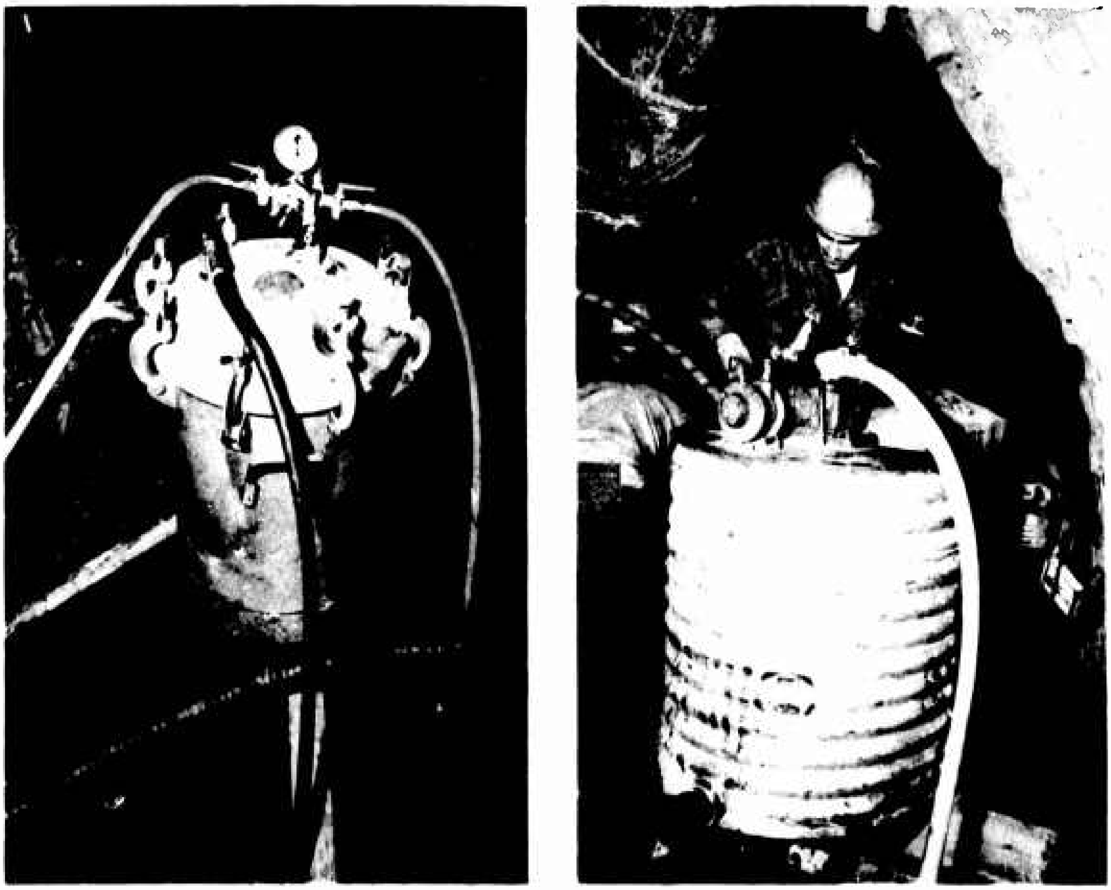


Figure A.1 Concrete formwork.



a. Foam generator. b. Tub-type grout mixer.

Figure A.2 Foaming and mixing equipment.

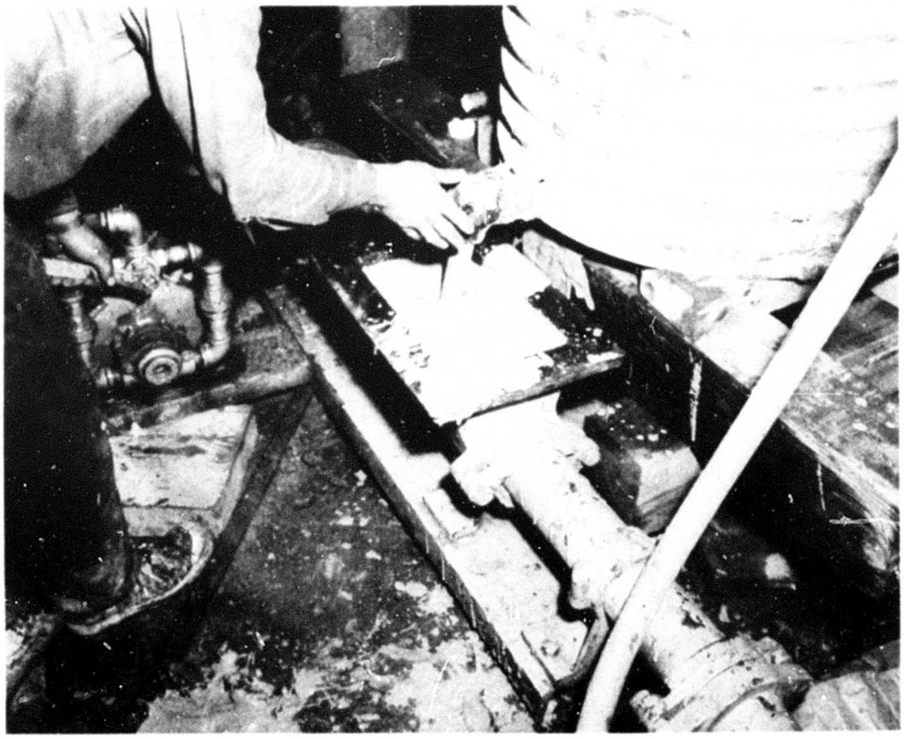
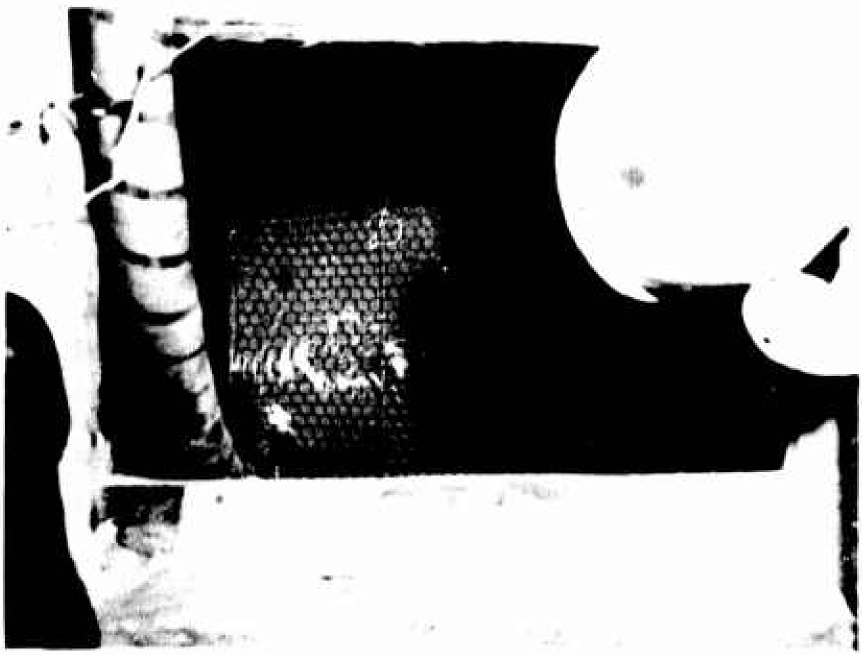


Figure A.3 Cellular concrete discharging into an open-throat pump.

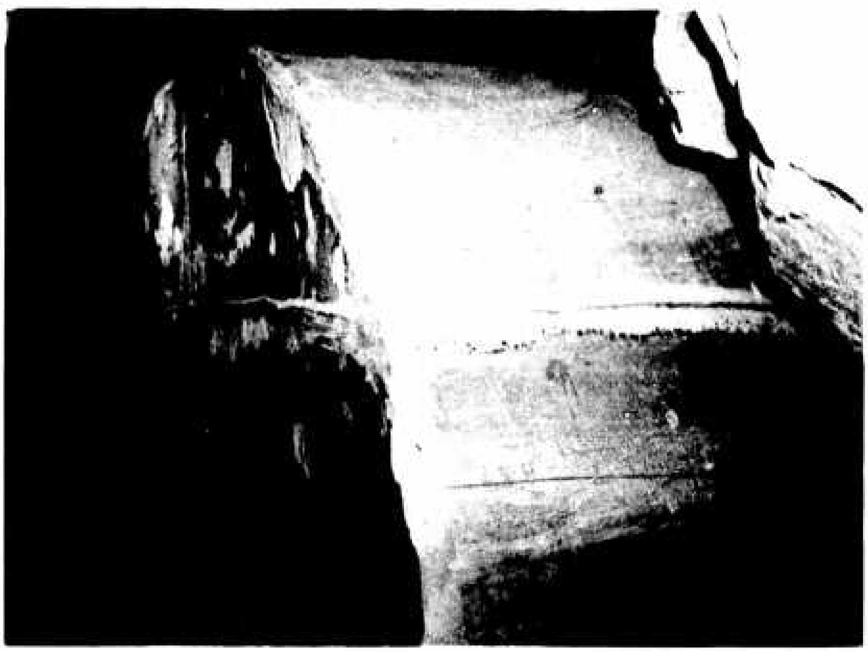
a. Overall view of opening.



b. Closeup of opening showing surface of freshly placed cellular concrete.

Figure A.4 Views of opening in formwork for placing concrete.

a. Left side.



b. Right side.

Figure A.5 Entire hardened concrete section.

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13. ABSTRACT

The objective of this study was to investigate three insulating concretes being considered for use as a backpacking material to determine their handling, mixing, and placing characteristics, as well as the density variation, plastic shrinkage, aggregate segregation, and rate of hardening occurring in large sections made with each concrete, and to determine the problems that may be associated with the use of these concretes in a prototype situation. Metal, half-scale model sections of a typical rock opening and tunnel liner were used in the study. The annular space of each section was pumped full or partially full of cellular, vermiculite, or polystyrene concrete. Each concrete was evaluated on the basis of ease of handling, batching, and placing and on the density variations occurring in both the unhardened and hardened condition of the concrete. In situ density variations were studied by the use of three techniques: ultrasonic pulse velocity, heat development, and hardened concrete samples. Fresh concrete unit weights were used for the unhardened concrete quality control. Rate-of-hardening tests were conducted to aid in the estimation of form-removal times. Methods of reducing plastic shrinkage and bleeding are discussed, along with other features such as handling and storage requirements of mixture components and suggested prototype batching and placing equipment and techniques. An appendix describes a field placement trial of a cellular concrete arch section to determine the ease of placing and forming, required strength for arch to stand unsupported, and settlement of arch crown.

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